FLUID MANAGEMENT
SYSTEMS TECHNOLOGY SUMMARIES

December 1974

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GENERAL DYNAMICS
Convair Division

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16. Abstract

This report presents a summarization and categorization of the pertinent literature associated with fluid management systems technology having potential application to in-orbit fluid transfer and/or associated storage. Initially, a literature search was conducted to obtain pertinent documents for review. Reports determined to be of primary significance were summarized in detail. Each summary, where applicable, consists of; (1) report identification, (2) objective(s) of the work, (3) description of pertinent work performed, (4) major results, and (5) comments of the reviewer (GD/C). Pertinent figures are presented on a single facing page separate from the text. Specific areas covered are; fluid line dynamics and thermodynamics, low-g mass gauging, other instrumentation, stratification/pressurization, low-g vent systems, fluid mixing, refrigeration and reliquefaction, and low-g interface control and liquid acquisition systems. Reports which were reviewed and not summarized, along with reasons for not summarizing, are also listed. Low-g fluid behavior and cryogenic thermal control technology are presented in companion reports (NASA CR-134746 and NASA CR-134747) under this same contract.

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FOREWORD

This report was prepared by the Convair Aerospace Division of General
Dynamics Corporation in partial fulfillment of Contract NAS3-17814.
The contract was administered by the Lewis Research Center of the
National Aeronautics Space Administration, Cleveland, Ohio. The NASA
Project Manager was Mr. John C. Aydelott.

A summarization and categorization is presented of the pertinent litera-
ture associated with fluid management systems technology having poten-
tial application to in-orbit fluid transfer and/or associated storage. Low-
gravity fluid behavior and cryogenic thermal control technology sum-
maries are presented in companion reports under this same contract.

In addition to the project manager, Mr. John A. Stark, a listing of the
Convair personnel which contributed to the preparation of this report,
along with their primary areas of responsibility, is presented below.

    J. A. Stark   -   General Fluid Management Systems, Stratification/
                               Pressurization, Vent Systems, Fluid Mixing, and
                               Refrigeration and Reliquefaction.

    F. O. Bennett   -   Fluid Line Dynamics and Thermodynamics.

    B. J. Campbell -   Mass Gauging and Other Instrumentation.

    M. H. Blatt   -   General Interface Control and Liquid Acquisition
                               Systems, Capillary Acquisition, Positive
                               Expulsion Systems and Other Liquid Acquisition
                               Systems.

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1.0 INTRODUCTION

This report presents a summarization and categorization of the pertinent literature associated with fluid management systems technology having potential application to in-orbit fluid transfer and/or associated storage.

The initial task was to conduct a literature search to obtain pertinent documents for review. The following sources formed the primary basis for this search.

   a. Convair Library and Cryogenic Group files.

   b. "Bibliography of References — Space Storage of Cryogenic Propellants, " (Report B-777) prepared by the Cryogenic Data Center, NBS, covering the period 10 June 1974 back through 1959.

   c. NASA-computer tape search for the period 30 September 1974 back through 1969. Key words used in this search are presented in Appendix C.

   d. "The Literature of Low-G Propellant Behavior, " by Bowman (NAS9-8939, September 1969) and "The Literature of Low-G Propellant Behavior, " by Hastings, et al (NAS9-5174, September 1966). These two documents together cover the period August 1969 back through 1959.

   e. Defense Documentation Center (DDC) search of the unclassified literature for the period 3 June 1974 back through 1969.

   f. Secondary sources from reports reviewed.

Reports which were determined to be of primary significance are summarized in Sections 2 through 13. Each summary, where applicable, consists of; (1) report title, author(s), organization doing the work, identifying numbers and date, (2) objective(s) of the work, (3) description of pertinent work performed, (4) major results, and (5) comments. The thoughts expressed by the objective, pertinent work performed, and major results sections are those of the author. The thoughts of the reviewer (GD/C) are presented in the comments section. Pertinent figures are presented on a single facing page separate from the text. Units used in the summaries are those from the basic report; i.e., dual units were only used if they were in the report being summarized. Where a reference is cited within the summary, the author(s) and date were used in place of a reference number. Uncommon abbreviations, acronyms and nomenclature are defined in the individual summaries, while general definitions and nomenclature are presented in Appendix D.

The summaries are organized by category and date, with the most current work appearing first. Also, a listing of all summarized reports alphabetically by author is presented in Appendix A.

The categories into which the summaries are divided are listed below, along with a brief description of the work covered in each.

a.   Fluid Management Systems (General) — covering overall space storage and/or fluid transfer systems data which may be pertinent to in-orbit resupply and which do not fit into any of the following categories or contains information on more than one.

b.   Fluid Line Dynamics and Thermodynamics — covering start/shutdown transients, two-phase flow surging, pumping, pressure drop and critical flow or choking, and line chilldown.

c.   Mass Gauging — covering the various aspects of determinig fluid quantity at low-g.

d.   Other Instrumentation — covering liquid/vapor sensing at low-g, flowmetering, two-phase flow quality gauging, and temperature and acceleration measurement.

e.   Stratification/Pressurization — covering fluid temperature stratification and tank pressurization with and without liquid outflow, with and without external pressurization with condensible and/or non-condensible gases, and with and without venting.

f.   Vent Systems — covering analysis, design, fabrication and test of systems to vent and/or control fluid storage and/or receiver tank pressures at low-g.

g.   Fluid Mixing — covering analysis, design fabrication and test of systems to destroy fluid temperature stratification and/or minimize tank pressure rise by fluid mixing.

h.   Refrigeration and Reliquefaction — covering systems to control tank pressure of space-stored fluids through refrigeration and/or reliquefaction.

i.   Interface Control and Liquid Acquisition Systems (General) — covering systems and studies which consider various aspects of more than one of the following categories.

j.   Capillary Acquisition — covering analysis, design, fabrication and test of systems using surface forces to control liquid orientation.

k.   Positive Expulsion — covering bladders, bellows, diaphragms and pistons, with expanding or contracting surfaces to control orientation and/or to allow liquid expulsion at low-g.

1. Other Interface Control and Liquid Acquisition Systems – covering the use of centrifugal, electrical, and acoustic forces for liquid control.

Reports which were reviewed and not summarized, along with reasons for not summarizing, are listed in Appendix B. The following ground rules were used in selecting specific reports for summarization.

a. Only that work having potential application to in-orbit fluid transfer and/or associated storage was included; e.g., under fluid line dynamics and thermodynamics all two-phase flow literature was not included.

b. Both non-cryogenic and cryogenic applications were considered.

c. The report must have provided data required for current design and/or added something important to the knowledge required to provide a complete picture of the current state-of-the-art.

d. Emphasis was on the most recent work; however, reports were not summarized if they were just a rehash of other work. If they were primarily connected with other work they must have provided useful consolidations, additions or evaluations.

e. Fluid tankage itself and associated structural details were not included.

f. Monthlies, Quarterlies and classified reports were not summarized.

g. Reports which are not generally available were not included, such as symposium papers where only those in attendance may have copies, and internal company documents such as Independent Research and Development (IRAD) reports.

2.0 FLUID MANAGEMENT SYSTEMS (GENERAL)

Covering overall space storage and/or fluid transfer systems data which may be pertinent to in-orbit resupply and which do not fit into any of the following categories or contains information on more than one.

IN-SPACE PROPELLANT LOGISTICS
Sexton, R. E., et al, NAR, SD 72-SA-0053,
NAS8-27692, June 1972

OBJECTIVE. - Definition of a representative in-space propellant logistics system and its operation.

PERTINENT WORK PERFORMED. - Work included determination of in-space propellant requirements in support of the NASA space program plan (Fleming Model), definitions of propellant logistics system concepts to meet these requirements, cost analyses and maintenance, and manned support requirements analyses. This work is reported in five volumes; (1) executive summary, (2) technical report, (3) trade studies, (4) project planning data, and (5) cost estimates. A systems safety analysis was also accomplished and is reported in another three volumes under report number SD 72-SA-0054.

In general, the work reported here is based on existing technology or work which is summarized elsewhere. However, a few pertinent notes of current interest are presented below.

MAJOR RESULTS. -

1. The connected ullage concept shown in Figure 1 was selected as the baseline system for receiver tank thermodynamic control on the basis of minimum propellant loss, system simplicity, and compatibility with the expulsion subsystem selected. Liquid acquisition is accomplished with linear acceleration.

2. Pullthrough data developed in another study (Chen and Zukoski, 1968) was used to compare a variety of tank outlet shapes. Residuals versus Froude number are shown in Figure 2 for various tank geometries. Data from Chen and Zukoski, 1968, indicated that residuals would be two to four times greater than predicted by Berenyi and Abdalla, 1970. The selected configurations employed flow rate throttling of 10:1 to reduce residuals.

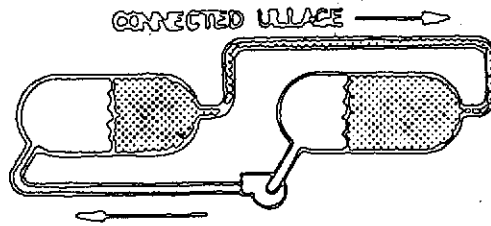COMMENTS. - Chen and Zukoski, 1968, was not obtained in time to be included in the literature review.
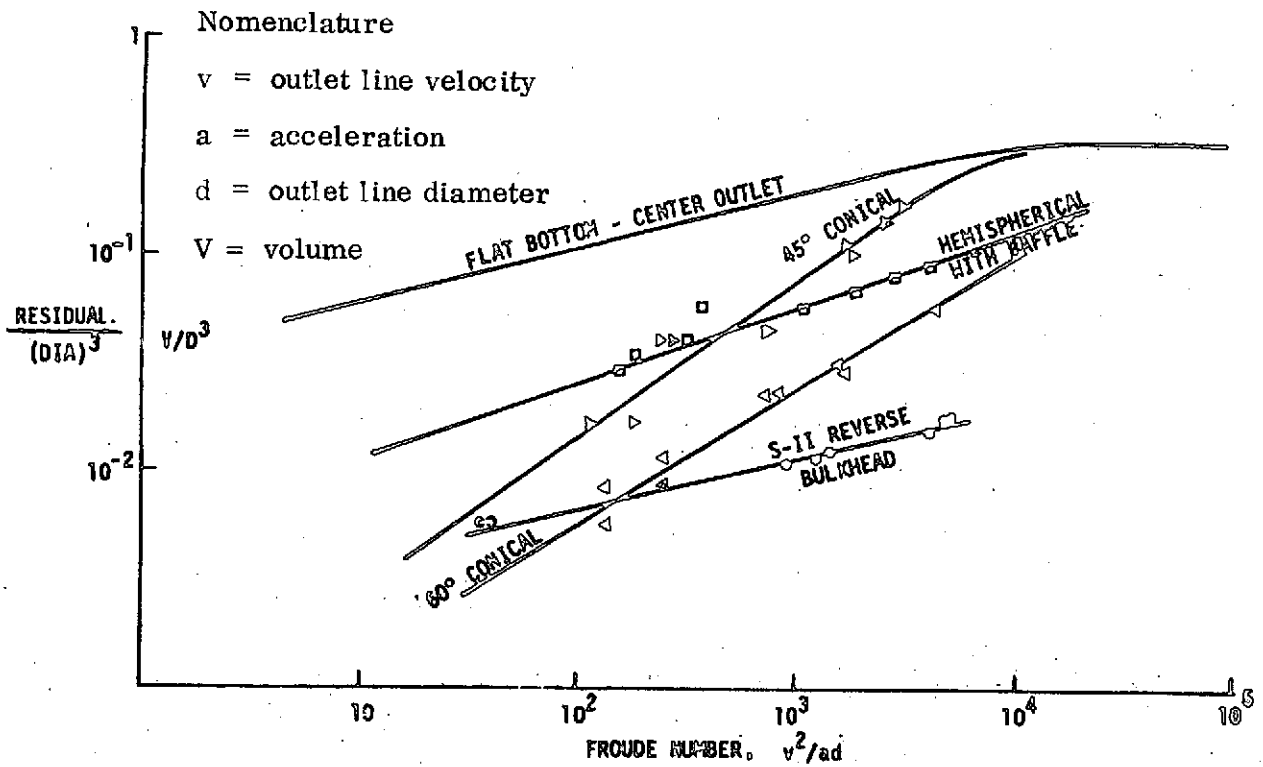
Figure 1. Connected Ullage

Figure 2. Residual Versus Froude Number for Various
Tank Geometries

STUDY OF LOW GRAVITY PROPELLANT
TRANSFER- FINAL REPORT, Stark, J. A.,
GD/C, GDC-DDB72-002, NAS8-26236, June 1972

OBJECTIVE. - To perform an analytical assessment of potential methods for replenishing
the auxiliary propulsion H_2, O_2 and N_2 cryogens which may be aboard an orbiting space
station.

PERTINENT WORK PERFORMED. - This study included storage of supply fluid, transfer,
and receiver tank pressure and temperature control. Systems considered were
high pressure (supercritical), subcritical, and modular (transfer of the tanks). The
baseline resupply requirement was 1,096 lb of H_2, 2480 lb of O_2 and 3,150 lb of N_2
to eight H_2, two O_2 and two N_2 bottles. The standard receiver tank was a 42.5 ft^3
sphere containing liquid at 100 psia for station use. In addition to the baseline conditions,
weight and performance data were generated for bottle diameters from 25 to 150-in.
and transfer fluid quantities from 500 to 5,000 lb of H_2 and 1,000 to 10,000 lb each of
O_2 and N_2. Transfer line lengths were 20 to 200 ft. and the maximum disturbing
acceleration was 10^{-4}g's. Both individual supply tanks for each receiver and a single
supply for each fluid were considered.

Capillary screen, dielectrophoresis, bladders, bellows, diaphragms, and fluid vortexing
methods of subcritical transfer were initially considered. On the basis of safety, weight
and development potential only screen, metallic bellows, metallic diaphragm and paddle
vortex sub-critical systems were selected for detailed analysis. The dielectrophoretic
system was not chosen primarily on the basis of potential safety, since in O_2 there is
still some question of electrical breakdown and combustion hazard associated with this
high voltage system. Line and tank chilldown data are also presented and the feasibility
of non-vent transfer was investigated for various operating conditions.

MAJOR RESULTS. -

1. Analysis of various high pressure supply heating and blowdown and receiver cooling
   schemes showed the only concept worthy of any consideration was one employing
   simple supply heating with increased receiver volume to allow for the reduction in
   transferred fluid density. Also, the final receiver fluid cannot be liquid since any
   requirement for condensation results in excessively high weight and power.

2. The surface tension and paddle systems were determined, on the basis of low weight·
   and cost and high reliability and reusability, to have the best potential for the space
   station application. Typical system weight data are presented in Figure 1. Receiver
   tank weights are divided by 20 to reflect the fact that the receiver tanks stay fixed
   on the station for 20 supply cycles. Individual receiver weights are presented in
   Figure 2. The paddle vortex concept is illustrated in Figure 3.

COMMENTS. - The bellows work is reviewed under a separate summary.

Figure 1. Total H₂ Transfer System Weight (Supply + Receiver/20)

Figure 1 labels: TOTAL SUPPLY FLUID PLUS RECEIVER RESIDUAL INCLUDED; HIGH PRESSURE 1 HR TRANSFER; HIGH PRESSURE 24 HR TRANSFER; SUBCRITICAL SURFACE TENSION AND PADDLE; MODULAR; MODULAR; H₂ MASS TRANSFERRED, lb; WEIGHT, lb

Figure 2. Receiver Weights for H₂ Transfer

Figure 2 labels: ONLY RESIDUAL FLUIDS INCLUDED; HIGH PRESSURE; MODULAR; SUBCRITICAL; H₂ MASS TRANSFERRED, lb; WEIGHT, lb

Figure 3. Paddle Type Vortex System

Figure 3 labels: MLI; ROTATION; LIQUID OUTLET; PADDLE BLADES; TANK WALL; MOTOR DRIVE ASSEMBLY

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REVIEW OF ORBITAL PROPELLANT TRANSFER TECHNIQUES
AND THE FEASIBILITY OF A THERMAL BOOTSTRAP
PROPELLANT TRANSFER CONCEPT
Yoshikawa, H.H., Madison, I.B., Aerospace Corp.,
ATR-72(7235)-7, NASW-2129, December 1971

OBJECTIVE. - Report on the findings and recommendations of existing literature on
space-based propellant transfer techniques and determine possible alternatives.

PERTINENT WORK PERFORMED. - Results of the literature review showed that the
recommended in-orbit transfer technique was, in general, the use of conventional
liquid transfer (i.e., pumping) in conjunction with an artificially induced gravitational
field.

Under the current program an analytical study was made of the feasibility of a "Thermal
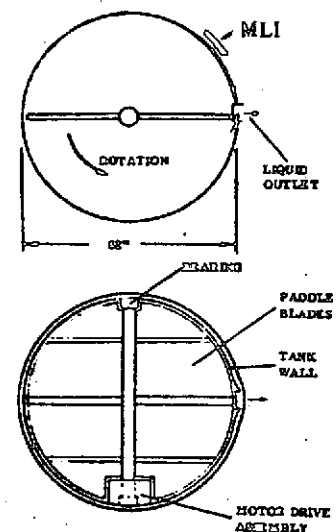Bootstrap Transfer Process" as shown in Figure 1. Referring to Figure 1, the fluid
is stored at equilibrium saturated conditions along the line E-E', at state point 1.
This assumes no noncondensables; a requirement of this system. From state point 1,
the fluid is introduced to a header where the temperature and pressure decrease along
a constant enthalpy line to state point 2. The fluid is then compressed to a suitable
state point, 3, such that its pressure and corresponding temperature differential allows
the transfer of the heat of vaporization to the donor tank residual. After condensation
the transfer fluid is subcooled to state point 4. The heat rejected between 3 and 4 is
absorbed by the bulk supply fluid, causing evaporation from states 1 to E'. It is
assumed that there is sufficient evaporation within the supply to maintain constant
temperature and pressure. The process in the receiver tank follows two paths; (1)
from points 5 to 6, where the fluid is retained in the liquid state by preventing its
contact with the warm tank walls and (2) the fluid which is directed laterally contacts
the tank wall and vaporizes to points 7 and 8. The fluid after expansion in the turbine
is at state point 9. This turbine is used for fluid pumping from states 2 to 3.

MAJOR RESULTS. -

1. Calculations for hydrogen transfer indicated the thermodynamic feasibility of the
   process. This was based on a donor tank of 12,000 ft^3, initially 95% full of liquid
   and transferring 8500 lb of LH$_2$ to a 400°R receiver tank.

2. Even though, for certain conditions, there is sufficient total receiver tank energy
   available, the available rate does not coincide with the demand rate, meaning the
   produced energy must be controlled, stored,or an auxiliary source, such as a
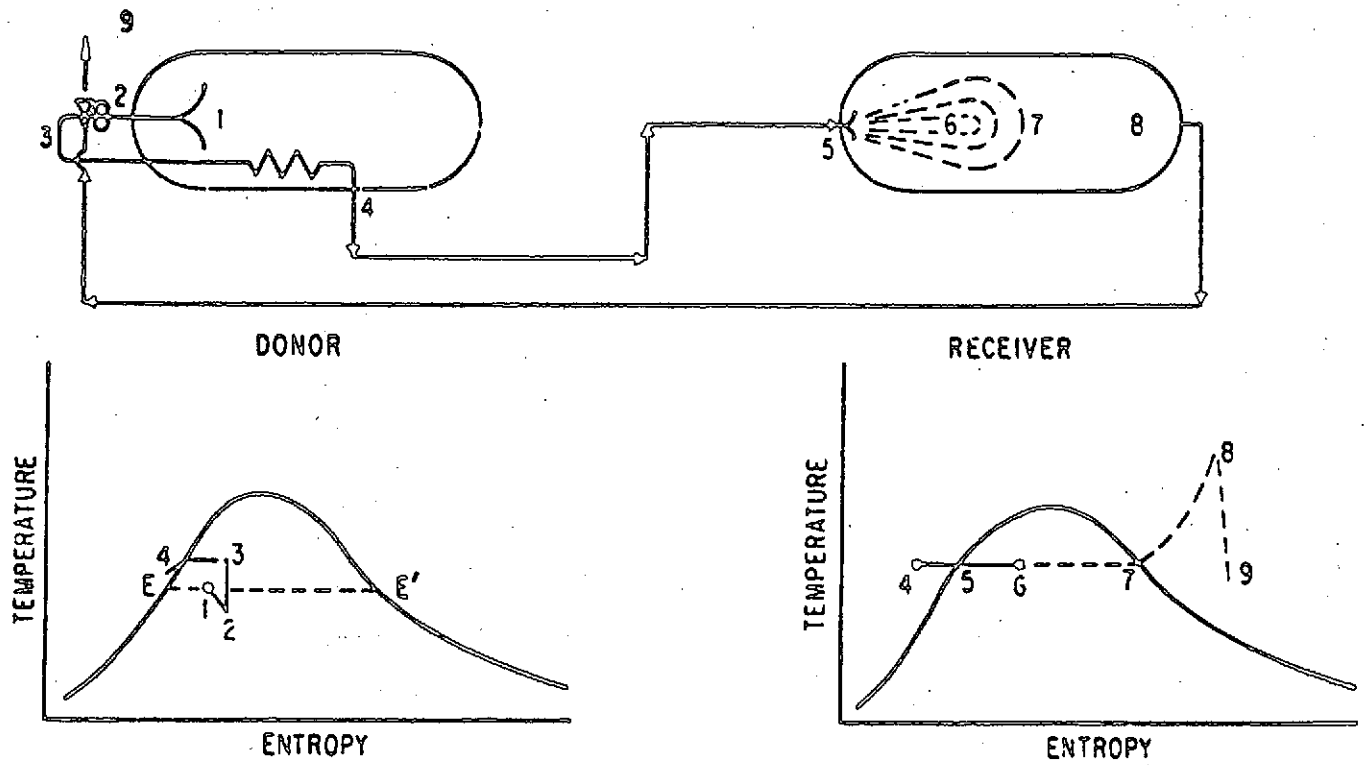   gas generator used to heat the H$_2$ gas.

Figure 1.   Transfer Process Schematic

3.0 FLUID LINE DYNAMICS AND THERMODYNAMICS

Covering start/shutdown transients, two-phase flow surging, pumping, pressure drop and critical flow or choking, and line chilldown.

WATERHAMMER AND SURGE CONTROL
Streeter, V.L., Wylie, E.B., Univ. of Michigan,
Annual Review of Fluid Mechanics, Vol. 16, 1974.

OBJECTIVE. - To review waterhammer and surge phenomena and discuss techniques
for analyzing the transient-flow problems.

PERTINENT WORK PERFORMED. - The initiation and propagation of hydraulic
transients is discussed. A review of pressure-pulse wave transmission investigations
is presented. Two types of analytical approaches to the problem are reviewed; the
"operational" method and the "numerical" method. In the operational method, the
system propagation value and characteristic impedance are the most useful parameters
for characterizing the fluid pipeline response. Models of differing degree of sophisti-
cation have been developed to handle specific problems. Figure 1 shows typical predicted
transient responses for models with (a) no dissipation, (b) a linearized viscous loss
(friction) term, and (c) both viscosity and heat transfer taken into consideration.
Selecting a model for a particular application depends on the objective of the study,
the values of pertinent dimensionless numbers, and the type of boundary conditions.

The numerical solution methods utilize finite-difference techniques to solve non-linear
equations. Either the implicit technique, requiring simultaneous solution of a large
number of equations, or the explicit technique, in which pressure and flow are
determined incrementally at the computing sections, are used. The implicit procedure,
while not limited to small time steps, can become very complex when a large number
of equations are involved.

MAJOR RESULTS. -

1. The operational method offers advantages when the objective is to determine the
   system frequency response and resonating characteristics.

2. The numerical method is more flexible with regard to interfacing simple or
   complex pipeline systems with arbitrary boundary excitations.

3. The uncertainty of the acoustic speed during a transient is the greatest source
   of computational error. Only one-tenth percent of air by volume in a liquid can
   reduce the wavespeed by half.

4. Theory is available to devise valve motions or pump starting procedures which
   will minimize the effects of transients.

5. Devices such as accumulators, relief valves, surge tanks, etc. are available
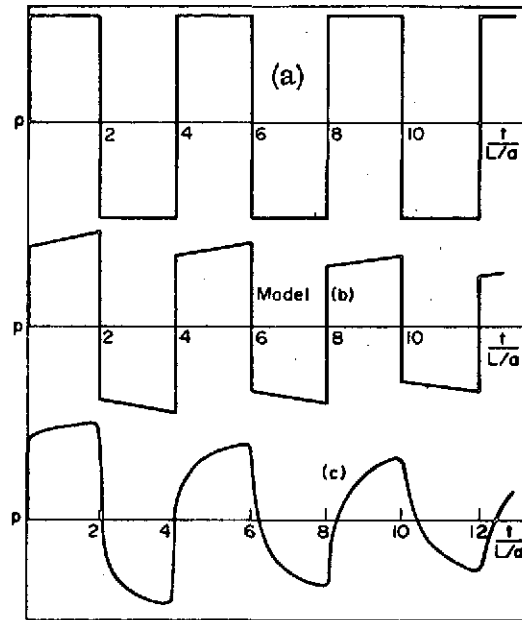   to reduce pressure fluctuations.

Figure 1.   Transient response at valve in
single pipeline

AN EXPERIMENTAL INVESTIGATION OF TWO-PHASE
LIQUID OXYGEN PUMPING
Gross, L. A., NASA-MSFC, TN D-7451, November 1973

OBJECTIVE. – To demonstrate the feasibility of pumping two-phase oxygen using a flight-configured (J-2) liquid oxygen pump.

PERTINENT WORK PERFORMED. – An analysis was performed of the J-2 engine liquid oxygen turbopump which indicated that at a speed approximately half the nominal 8000 rpm, the pump would operate in the two phase region. A blade blockage factor of 25 percent was predicted. Both high- and low-speed cavitation tests were performed to verify predicted performance. After attaining steady-state operating conditions, pump cavitation was initiated by slowly reducing the pressure in the run tank. Tests were continued until at least ten percent head loss had occurred. Nineteen successful tests were conducted, nine at speeds ranging from 6800 to 7650 rpm, and ten from 4320 to 4440 rpm. Two-phase operation was not achieved at the higher pump speeds, as predicted. Figure 1 shows a modified head coefficient plotted against net positive suction head (NPSH) for the high speed runs. The pump operated at progressively lower NPSHs as the liquid bulk temperature was increased. Two-phase conditions were successfully achieved during the final ten runs at the lower pump speeds. Figure 2 shows the results using a split abscissa, the right side being the pump inlet pressure minus the propellant vapor pressure, and the left side the percentage of vapor by volume at the pump inlet after two-phase conditions had been achieved. The experimental vapor handling capability of the pump was found to be significantly greater than predicted. Blade blockage of less than ten percent would be required (compared with the predicted 25 percent) to achieve the experimental vapor handling capability. No factors which could account for this discrepancy were found.

MAJOR RESULTS. –

1. The feasibility of pumping two-phase oxygen was demonstrated.

2. Using a standard J-2 engine turbopump, pump inlet vapor percentages of up to 50 were achieved before a ten percent reduction in pumping efficiency was encountered.

3. A practical two-phase pumping system for liquid oxygen could be developed.

Figure 1 (chart):

Y-axis: $\Delta H/N^2$ (m/rpm^2 x 10^6)
Values: 10.0, 9.0, 8.0, 7.0

X-axis: NPSH(m), values 0 1 2 3 4 5 6 7 8 9 10 11

Curve labels: 2,4 ; 3,5 ; 4 ; 3 ; 2 ; 5

NOTES:

1. Q/N =1.211 x 10^{-3} m^3/rov

2. DATA PLOTTED AT 7650 rpm

3. CURVE NUMBERS REFER TO TEST NUMBERS

Figure 1. Two-Phase Pump Performance

Figure 2 (chart):

Y-axis: $\Delta H/N^2$ (m/rpm^2 x 10^6)
Values: 10, 8, 6, 4, 2, 0

X-axis left: α = PERCENT VAPOR BY VOLUME, values 60 50 40 30 20 10 0
X-axis right: $P_{in} - P_{vap}$ (N/cm^2), values 0 1 2 3 4

Curve labels: 12,13,14,15,16 ; 15 ; 14 ; 16 ; 12 ; 15 ; 16 ; 13 ; 18 ; 14 ; 12

NOTES:

1. Q/N = 1.12 x 10^{-3} m^3/rov
2. TEST SPEED: 4400 rpm
3. CALCULATED PUMP INLET CONDITONS
4. CURVE NUMBERS REFER TO TEST NUMBERS
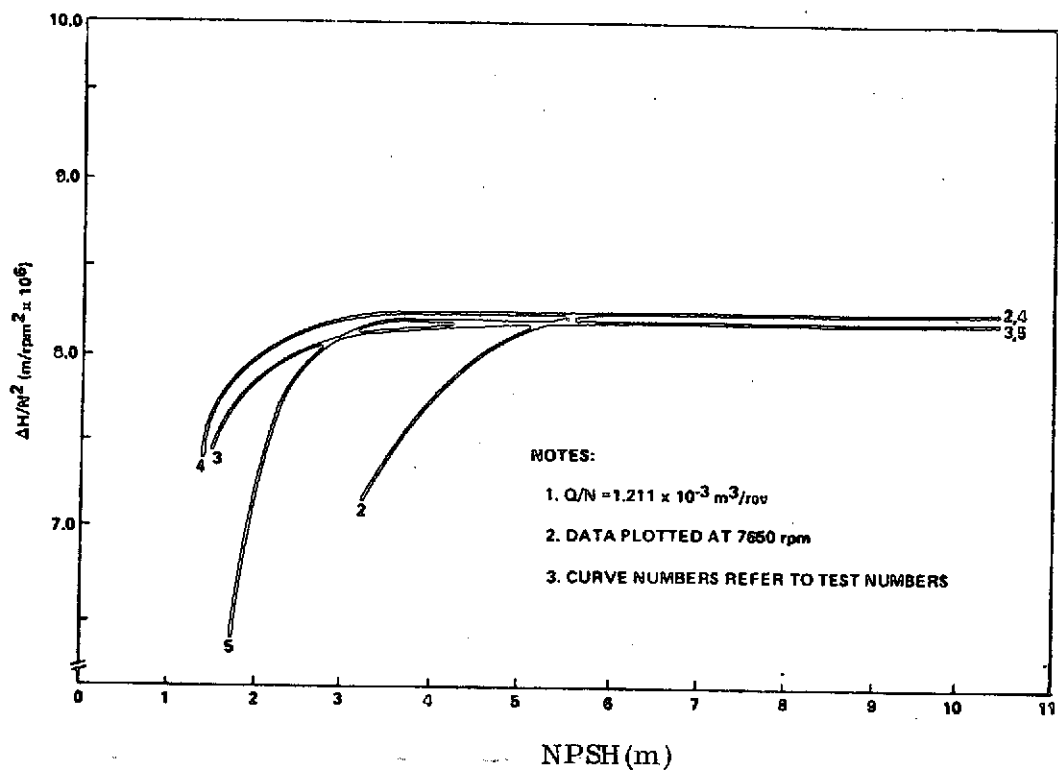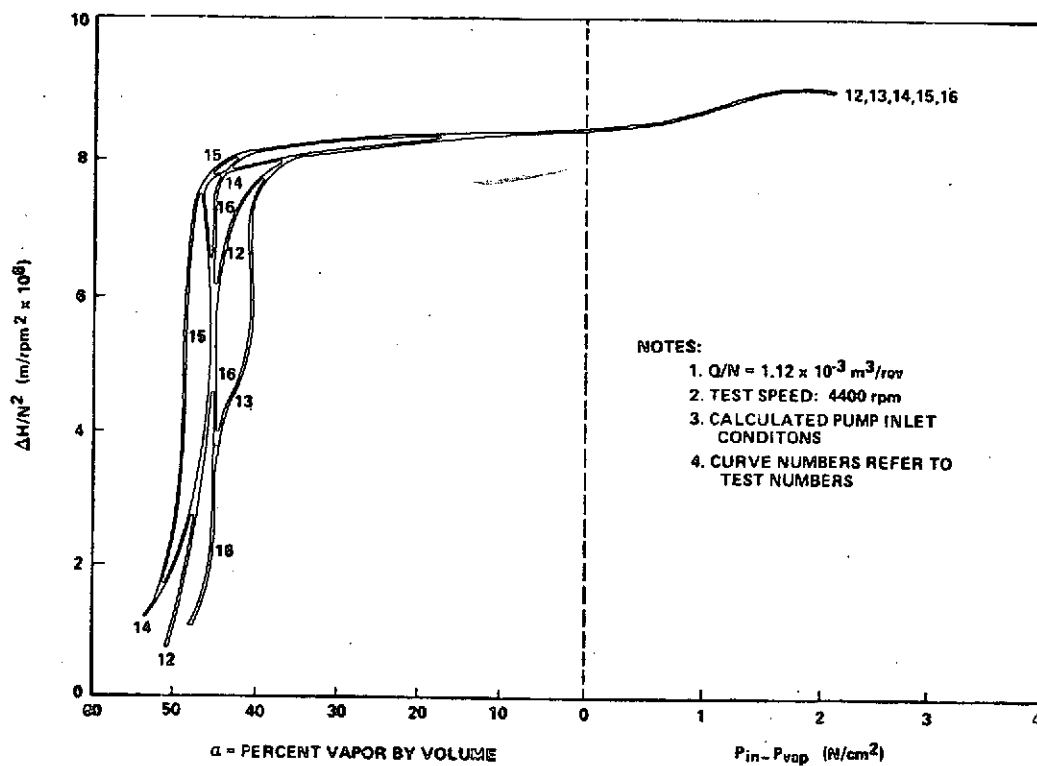
Figure 2. Pump Cavitation Performance

3-5

TRANSIENT FLOW IN CAPILLARY SYSTEMS

Gluck, D. F., NAR, SD 73-SA-0041, Contract
NAS7-200, March 1973

OBJECTIVE. - To analytically and experimentally investigate the effect of startup and
shutdown transients on capillary collectors.

PERTINENT WORK PERFORMED. - A basic experimental study of simply configured
capillary collectors (Figure 1) was conducted using horizontally mounted collectors and
subcooled monoflorotrichloromethane (Freon 11). The test configuration, simulating a
tank with a half-submerged collector tube, is shown in Figure 2. The collectors had a
square cross section (0.75" x 0.75") with three of the four sides of Lucite and the
remaining side of screen (Figure 3). The screened side was on top of the channel for
tests with 200 x 400 and 325 x 2300 mesh. For greater visibility, the screened side
was placed down for tests with 200 x 600 mesh screen. The length of feedline between
the test tank and the control valve varied from 6.2 to 38 feet. Control valve opening
times were 5 ms, 100 ms and 150 ms. An accumulator installed just upstream of the
control valve, was used to attenuate the pressure surges. An incompressible nonlinear,
viscous flow model was formulated specifically for analyzing gas ingestion during start
transients in the test configuration. A shutdown transient analysis terminated when test
results indicated that gas ingestion did not occur due to shutdown transients. Premature
termination of the study prevented correlation of the start transient model with test
results.

MAJOR RESULTS. -

1. High pressure surges due to shutdown did not produce like pressure surges in
   capillary collectors. Only trace amounts of vapor ingestion were observed in a
   few shutdown tests. Shutdown pressure surges were proportional to steady state
   flow rate and decreased with increasing valve opening time and accumulator
   volume. Although liquid spilling can occur due to shutdown transients, shutdown
   pressure surges do not appear to be a capillary device design problem.

2. Start transient flow caused substantial ingestion of gas into the capillary collector.
   Gas ingestion increased with increasing values of valve ΔP, and steady state flow-
   rate and decreased with increasing values of accumulator volume, line length,
   screen pore size, upstream line flow resistance and valve opening time.

COMMENTS. - Recent tests by Page, 1974, MMC (NAS8-30592), have indicated that
shutdown and start transients did not produce capillary device gas ingestion. A
comparison of the NAR results cited here and the Martin results was given in the 5th
monthly progress report of NAS8-30592. The shorter time duration of the pressure
spike above the bubble point and the lack of gas ingestion were explained by lower
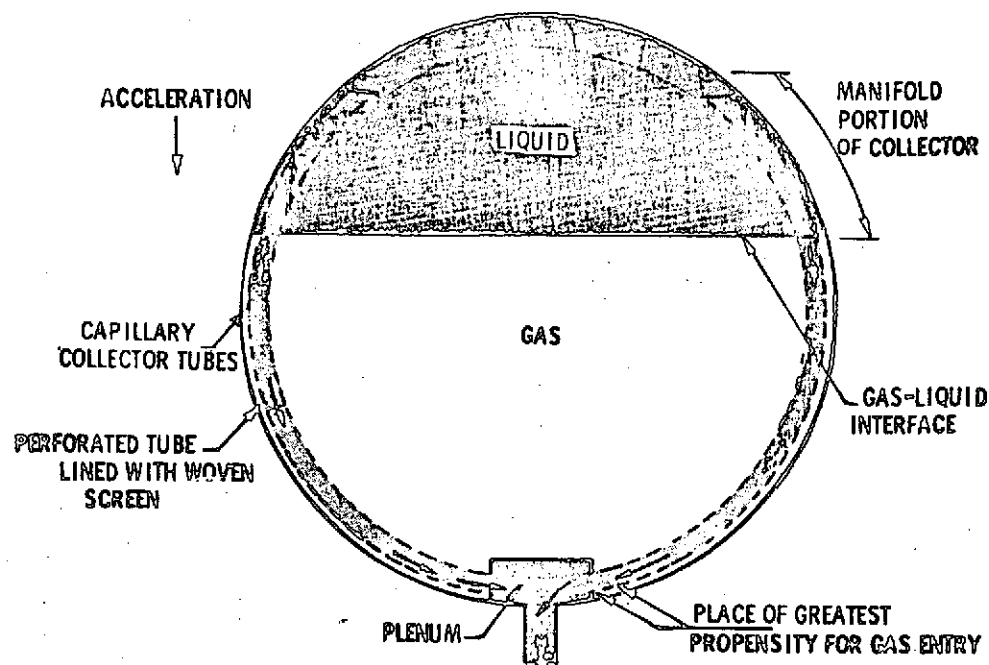fluid density and velocity in the Martin study.

Figure 1. Capillary Collectors for Propellant Acquisition Under an
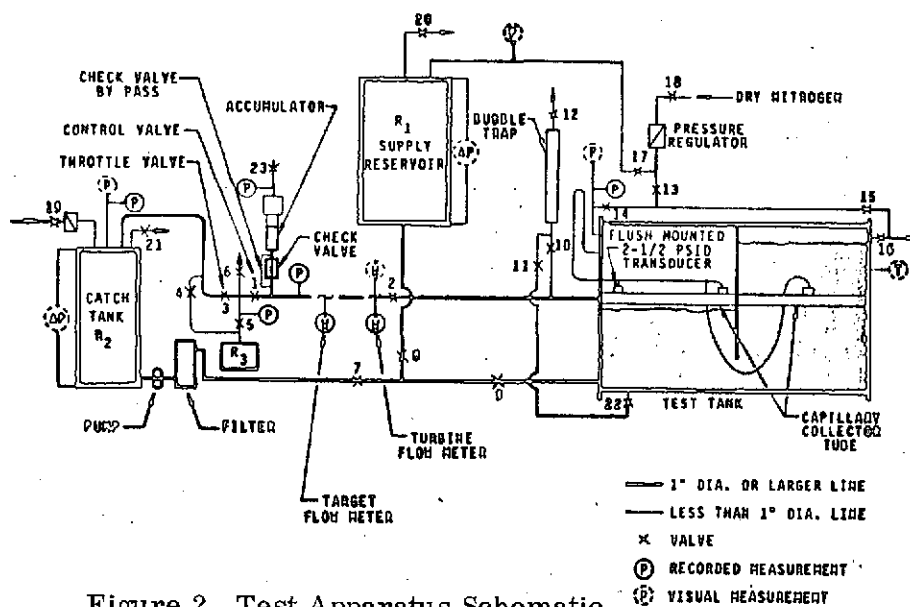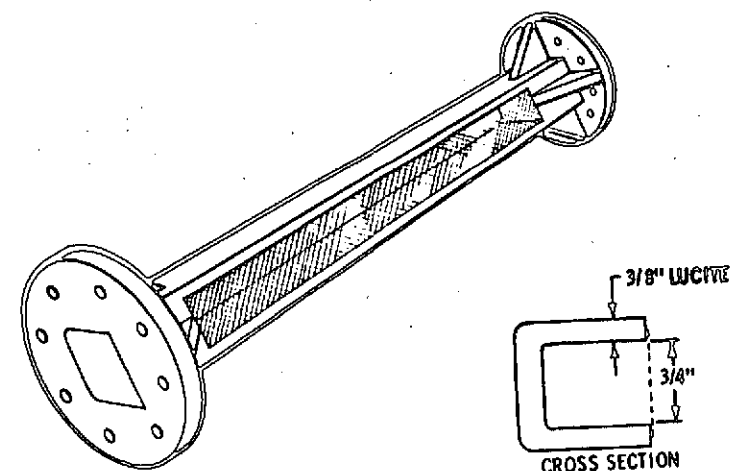Adverse Acceleration, Spherical Tank

Figure 2. Test Apparatus Schematic

Figure 3. Capillary Collector Tube

CRITICAL TWO-PHASE FLOW OF CRYOGENIC FLUIDS
Smith, R. V., et al, NBS TN-633, January 1973

OBJECTIVE. - To review analytical and experimental critical two-phase flow work since Smith (1962), and provide design recommendations and computational aids.

PERTINENT WORK PERFORMED. - Comparisons of critical single-phase and two-phase flow phenomena are made. Specific industrial applications where critical two-phase flow may be important are discussed. A thorough review of analytical models and experimental data for two-phase critical flow of fluids is presented. Most analyses approach the problem by starting with the well-understood critical flow of gases and incorporating differences or complications introduced by the presence of the liquid phase. Experimental results indicated that a description of liquid-gas distribution and flow velocities in all two-phase flows is difficult. Data in the critical flow region is essentially non-existent. A number of curves are presented showing predicted and measured critical mass flow rate as a function of fluid quality for various upstream pressures (Figure 1). It is left to the designer to choose the model that best fits his situation. In Figure 1, P_0 = stagnation pressure.

MAJOR RESULTS. -

1. The intuitive feel that critical two-phase flow velocities should lie somewhere between those of the gas and liquid in question is incorrect. Actual effective critical two-phase fluid flow velocity is much lower than that of either the gas or liquid.

2. With regard to critical two-phase flow, quality is a primary variable while system geometry is probably a secondary variable.

3. Although the assumptions of fluid homogeneity and thermal equilibrium are unlikely to be valid, models based on these assumptions produced reasonably good critical flow predictions.

4. The homogeneous mixture, non-equilibrium models (frozen flow) and the Henry (1968) model (Figure 1), appear to describe the critical flow process reasonably well. These models assume low mass transfer rates and low slip (gas-liquid velocity) ratios.

5. With respect to design utility, models which predict critical flows based on upstream (stagnation) conditions rather than on critical conditions, must be considered superior because data are much better known at the upstream location.

5000

$P_0 = 120 \ lb_f / in^2$
$(827.40 \ kN / m^2)$

10,000

1000

G_c , $lb_m / ft^2 \cdot s$

24.7 (170.30)

G_c , $kg / m^2 \cdot s$

1000

3.5 (24.13)

100

□ - $105 \geq P_0 \geq 135 \ lb_f / in^2$
○ - $24.3 \geq P_0 \geq 25.1 \ lb_f / in^2$
△ - $3.17 \geq P_0 \geq 3.79 \ lb_f / in^2$
——— Moody (1965, 1969)
--- Henry (1968)
Henry and Fauske (1971)

100
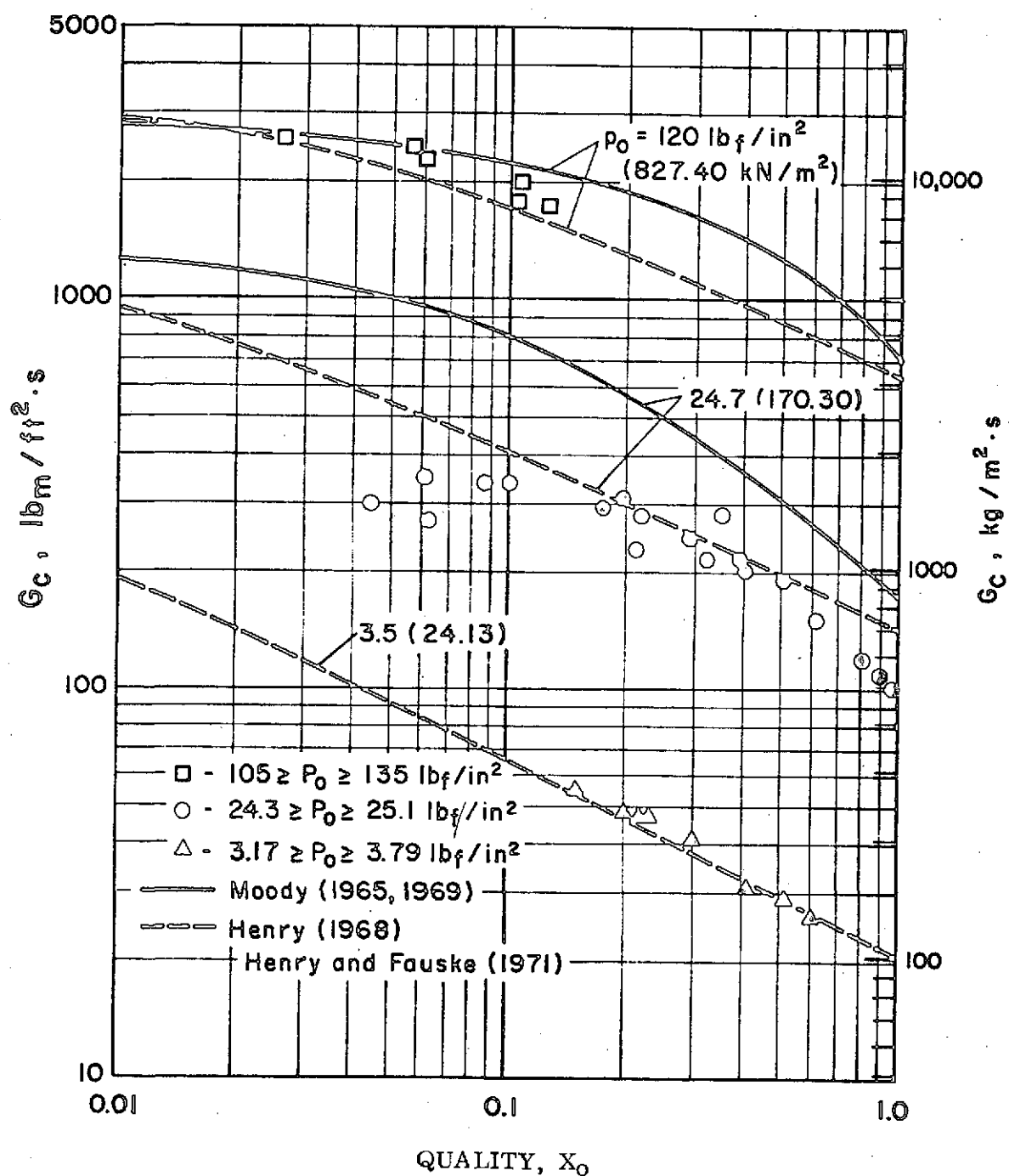
10

0.01

0.1

1.0

QUALITY, X_0

Figure 1. Two-phase orifice flow with nitrogen. Figure from Henry and Fauske (1971) with stagnation property curves of Moody (1965, 1969) added.

TWO-PHASE, TWO-COMPONENT CRITICAL FLOW IN A VENTURI

Smith, R. V., NBS, ASME Journal of Basic Engineering, March 1972

OBJECTIVE. - To test the hypothesis that the gas behavior primarily controls the critical (choking) and near-critical two-phase flow of two-component fluids for cases where essentially all the gas flows in separated and continuous streams.

PERTINENT WORK PERFORMED. - Experimental data were obtained with air-water mixture flows through an annular venturi. Both 0.0625 and 0.125-in. venturis were used. The ratio of liquid mass flow rate to gas mass flow rate was varied from 0.5 to 52.8, although visual observations indicated that the flow remained separated only to a mass flow ratio of 5. The measured critical pressure ratios varied from 0.52 to 0.62, approximately the values for isentropic and isothermal air flow, respectively. Shock waves in the diverging portion of the venturi exhibited behavior similar to that observed in all-gas flows. An analytical model was developed which consisted of a liquid film flowing at the tube wall and a gas core containing entrained liquid droplets. The sensitivity of calculated critical pressure ratios to variations in the parameters of droplet diameter, droplet drag coefficient, and interface heat transfer coefficient were found to be small. The effective gas flow area was adjusted to account for waves and droplet distribution through the use of an empirically determined blocking factor. A computation procedure was developed to numerically integrate the flow equations through the venturi using the Runge-Kutta method.

MAJOR RESULTS. -

1. The concept that the gas flow behavior controls two-phase, two-component critical flow for higher quality (gas fraction) flow rates is substantiated by the experimental and analytical results.

2. Comparisons between predicted and measured pressures in the venturi are excellent, even for the very low quality runs (Figures 1 and 2). The downstream endings of the analytical curves indicate the point of critical flow. In Figures 1 and 2, subscripts f, fe, ff and g refer to liquid, entrained liquid, liquid film and gas respectively.
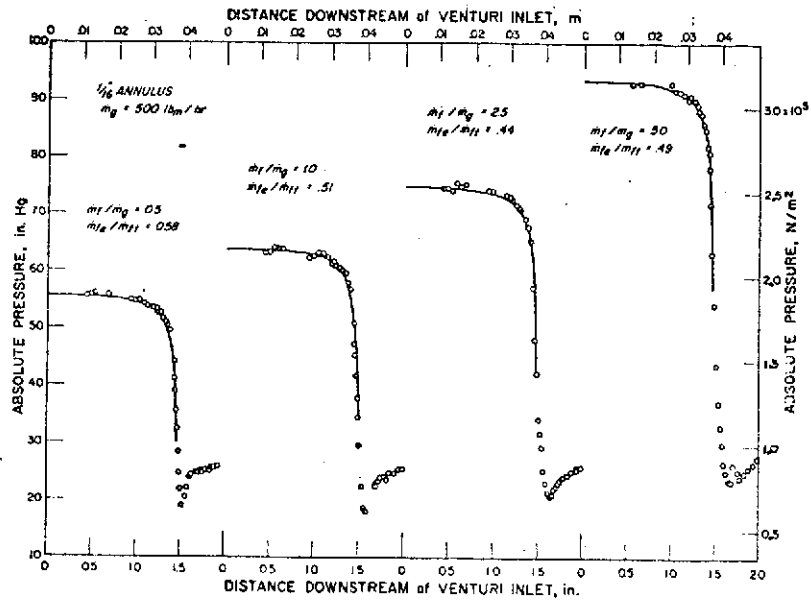
Fig. 1. Pressure versus axial distance along venturi. Analytical curves and experimental points for medium and higher quality flow rates, $\frac{1}{16}$ in. annulus venturi.
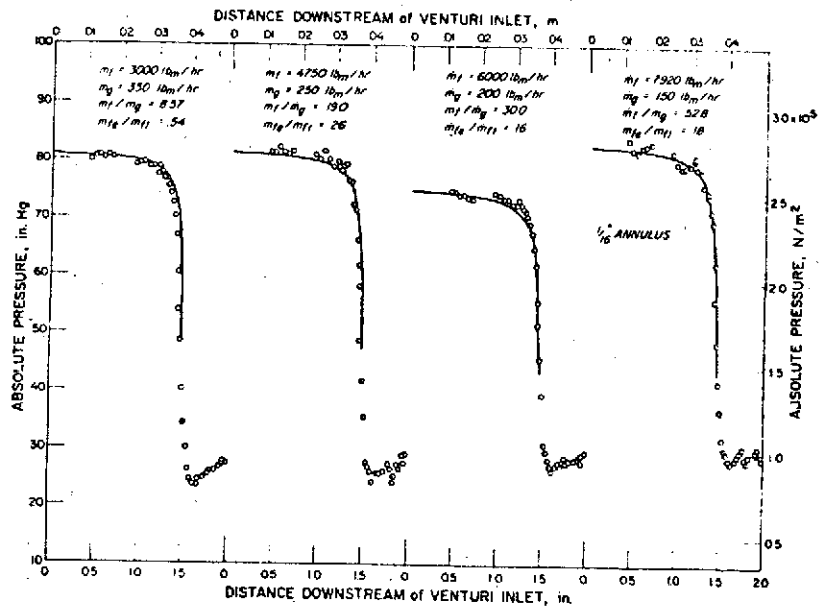

Fig. 2. Pressure versus axial distance along venturi. Analytical curves and experimental points for lower quality runs, $\frac{1}{16}$ in. annulus venturi.

TABULATED VALUES OF CAVITATION B-FACTOR FOR HELIUM
$H_2, N_2, F_2, O_2,$ REFRIGERANT 114 AND H_2O,
Hord, J., Voth, R. O., NBS, NBS-TN-397, February 1971

OBJECTIVE. - To establish an improved B-factor calculation method and to tabulate computerized results for several fluids of interest.

PERTINENT WORK PERFORMED. - A review is presented of various approaches for calculating the so-called "B-factor," defined as the ratio of the volume of vapor to the volume of liquid involved in the cavitation process. Although the "quasi-static" theory upon which the proposed solution is based is deficient from a theoretical viewpoint, it is well established and has been shown to provide good results (report references). The assumptions of the "quasi-static" model are the same as those for an isentropic process. Thus the time-consuming incremental pressure calculation process is eliminated. The B-factor is expressed solely in terms of fluid properties and is calculated in a one-step procedure. A comparison of the relationship between the saturation temperature depression due to vaporization and B-factor for the model presented in this report (solid line) and the more-rigorous (but still approximate) model of Gelder et al (1966) is shown in Figure 1 for LN_2.

The "quasi-static" model was used to calculate B-factors for the various fluids in the report title, from just above the triple point temperature to just below the critical temperature. A sample page for LH_2 is shown in Table 1. TF1 and PF1 are the initial liquid saturation temperature and pressure, respectively, and DTV and DPV are the reduction in the saturation properties of the liquid involved in the cavitation process. B is the B-factor. The error produced by successive linear interpolations in the table is shown to be less than ten percent.

MAJOR RESULTS. -

1. A simplified one-step, isentropic cavitation model is developed and shown to yield results similar to those of more rigorous, incremental-calculation models.

2. Tables of B-factors are provided over the full range of saturated liquid temperatures for He, H_2, N_2, F_2, O_2, H_2O, and Refrigerant 114 ($C_2 Cl_2 F_4$).

COMMENTS. - B-factor data are important for determining the relative ease with which various fluids can be transferred in the saturated state by pumping. For a particular transfer case the data is used to determine the actual driving pressure required to pump a given vapor fraction of two-phase fluid.

Table 1. B Factors for Parahydrogen

B FACTORS FOR PARAHYDROGEN

TF1 (R)	PF1 (PSIA)		DTV (R)	DPV (PSIA)	B
44.00	42.334				
			0.00	0.000	0.000
			0.35	1.771	0.111
			0.70	3.469	0.229
			1.05	5.154	0.356
			1.40	6.768	0.493
			1.75	8.332	0.639
			2.10	9.847	0.795
			2.45	11.313	0.963
			2.80	12.731	1.143
			3.15	14.103	1.336
			3.50	15.429	1.544
			3.85	16.709	1.766
			4.20	17.946	2.005
			4.55	19.139	2.261
			4.90	20.290	2.536
			5.25	21.399	2.832
			5.60	22.467	3.150
			5.95	23.496	3.492
			6.30	24.479	3.860
			6.65	25.433	4.256
			7.00	26.350	4.682
			7.35	27.231	5.142
			7.70	28.076	5.627
			8.05	28.886	6.161
			8.40	29.663	6.737
			8.75	30.407	7.361
			9.10	31.116	8.036
			9.45	31.799	8.766
			9.80	32.449	9.556
			10.15	33.069	10.417

TF1 (R)	PF1 (PSIA)		DTV (R)	DPV (PSIA)	B
43.50	39.620				
			0.00	0.000	0.000
			0.35	1.695	0.115
			0.70	3.339	0.238
			1.05	4.931	0.371
			1.40	6.474	0.513
			1.75	7.968	0.666
			2.10	9.413	0.830
			2.45	10.813	1.006
			2.80	12.163	1.195
			3.15	13.469	1.398
			3.50	14.731	1.616
			3.85	15.949	1.850
			4.20	17.124	2.102
			4.55	18.257	2.372
			4.90	19.348	2.663
			5.25	20.400	2.976
			5.60	21.412	3.314
			5.95	22.379	3.677
			6.30	23.317	4.068
			6.65	24.218	4.489
			7.00	25.084	4.944
			7.35	25.914	5.425
			7.70	26.710	5.955
			8.05	27.472	6.527
			8.40	28.202	7.147
			8.75	28.900	7.817
			9.10	29.566	8.545
			9.45	30.205	9.333
			9.60	30.812	10.190
			10.15	31.392	11.121

TF1 (R)	PF1 (PSIA)		DTV (R)	DPV (PSIA)	B
43.00	37.415				
			0.00	0.000	0.000
			0.35	1.622	0.126
			0.70	3.193	0.248
			1.05	4.714	0.367
			1.40	6.187	0.535
			1.75	7.612	0.695
			2.10	8.991	0.867
			2.45	10.323	1.052
			2.80	11.618	1.250
			3.15	12.852	1.464
			3.50	14.062	1.694
			3.85	15.208	1.941
			4.20	16.324	2.207
			4.55	17.398	2.493
			4.90	18.432	2.831
			5.25	19.421	3.133
			5.60	20.380	3.492
			5.95	21.302	3.878
			6.30	22.186	4.295
			6.65	23.038	4.736
			7.00	23.853	5.221
			7.35	24.635	5.746
			7.70	25.383	6.314
			8.05	26.099	6.929
			8.40	26.784	7.595
			8.75	27.436	8.320
			9.10	28.063	9.106
			9.45	28.658	9.960
			9.60	29.226	10.869
			10.15	29.766	11.902

TF1 (R)	PF1 (PSIA)		DTV (R)	DPV (PSIA)	B
42.50	35.113				
			0.00	0.000	0.000
			0.35	1.550	0.125
			0.70	3.050	0.259
			1.05	4.503	0.404
			1.40	5.906	0.560
			1.75	7.266	0.727
			2.10	8.579	0.907
			2.45	9.847	1.101
			2.80	11.071	1.310
			3.15	12.252	1.536
			3.50	13.398	1.776
			3.85	14.488	2.039
			4.20	15.545	2.320
			4.55	16.563	2.624
			4.90	17.535	2.951
			5.25	18.479	3.304
			5.60	19.385	3.685
			5.95	20.255	4.097
			6.30	21.090	4.534
			6.65	21.891	5.014
			7.00	22.658	5.535
			7.35	23.393	6.098
			7.70	24.096	6.709
			8.05	24.767	7.372
			8.40	25.408	8.092
			8.75	26.020	8.874
			9.10	26.604	9.726
			9.45	27.159	10.653
			9.80	27.686	11.664
			10.15	28.190	12.760

TF1 (R)	PF1 (PSIA)		DTV (R)	DPV (PSIA)	B
42.00	32.915				
			0.00	0.000	0.000
			0.35	1.480	0.130
			0.70	2.912	0.271
			1.05	4.296	0.422
			1.40	5.635	0.585
			1.75	6.929	0.761
			2.10	8.178	0.951
			2.45	9.383	1.155
			2.80	10.546	1.376
			3.15	11.667	1.613
			3.50	12.747	1.869
			3.85	13.787	2.146
			4.20	14.788	2.444
			4.55	15.745	2.766
			4.90	16.673	3.114
			5.25	17.563	3.490
			5.60	18.419	3.899
			5.95	19.239	4.329
			6.30	20.025	4.804
			6.65	20.778	5.320
			7.00	21.499	5.878
			7.35	22.188	6.485
			7.70	22.847	7.143
			8.05	23.475	7.860
			8.40	24.075	8.639
			8.75	24.646	9.487
			9.10	25.190	10.412
			9.45	25.787	11.422
			9.80	26.199	12.526
			10.15	26.665	13.733

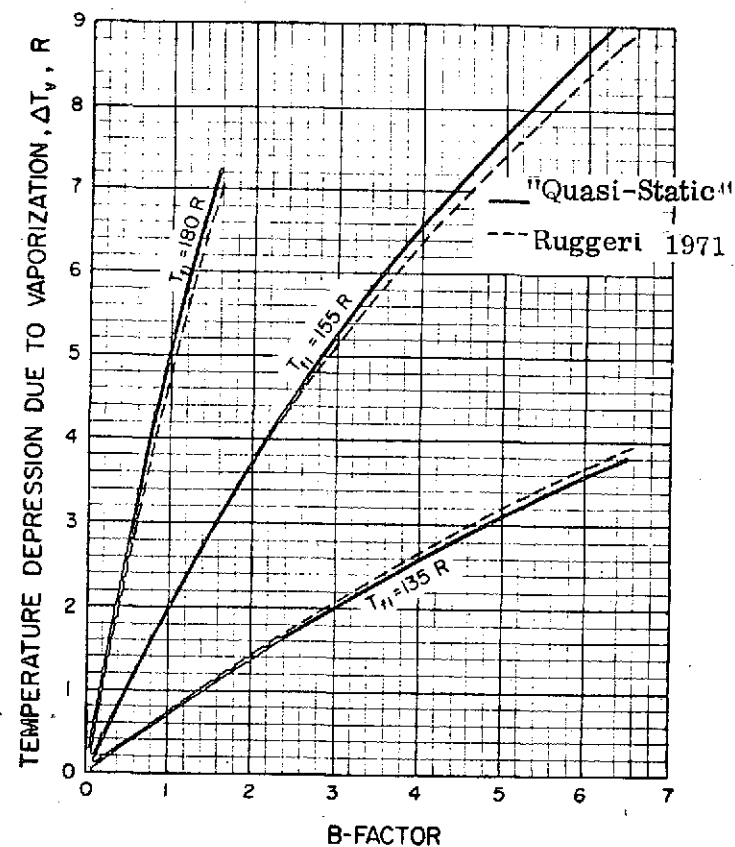| TF1 (R)	PF1 (PSIA)		DTV (R)	DPV (PSIA)	B
41.50	30.815				
			0.00	0.000	0.000
			0.35	1.412	0.136
			0.70	2.777	0.283
			1.05	4.096	0.442
			1.40	5.370	0.614
			1.75	6.600	0.799
			2.10	7.787	0.998
			2.45	8.932	1.214
			2.80	10.035	1.446
			3.15	11.098	1.697
			3.50	12.121	1.969
			3.85	13.099	2.252
			4.20	14.048	2.579
			4.55	14.960	2.921
			4.90	15.835	3.292
			5.25	16.675	3.687
			5.60	17.481	4.120
			5.95	18.253	4.591
			6.30	18.992	5.101
			6.65	19.699	5.658
			7.00	20.375	6.297
			7.35	21.020	6.911
			7.70	21.637	7.683
			8.05	22.224	8.390
			8.40	22.783	9.244
			8.75	23.316	10.166
			9.10	23.822	11.175
			9.45	24.302	12.877
			9.80	24.758	13.485
			10.15	25.190	14.809

Figure 1. B-factor and corresponding temperature depressions resulting from vaporization of liquid nitrogen

PRESSURE DROP OF TWO-PHASE FLOW IN A PIPELINE
WITH LONGITUDINAL VARIATIONS IN HEAT FLUX

Shen, P. S., Jao, Y.W., University of Toronto,
Advances in Cryogenic Engineering, Vol. 15, June 1969

OBJECTIVE. - To determine the pressure drop of two-phase nitrogen in a pipe with longitudinal variations in heat flux, and to compare results with those predicted by the Martinelli-Nelson (1948) correlation.

PERTINENT WORK PERFORMED. - Pressure drop in transfer systems is considerably higher for two-phase flow than it is for single-phase liquid flow, due to the reduction in flow area for each phase and the interaction of the phases. Tests were performed using liquid nitrogen flowing through uninsulated and partially insulated copper tubes of varying diameter to determine the effect on two-phase pressure drop. Results were tabulated and checked against the Martinelli-Nelson correlation (Figure 1). Here $\phi_{\ell tt}$ is the square root of the ratio of two-phase pressure drop to liquid phase pressure drop. The parameter X_{tt} is a function of liquid and gas phase densities and viscosities, and is inversely proportional to fluid quality (vapor fraction).

MAJOR RESULTS. -

1. The experimental results support the use of the Martinelli-Nelson correlation for two-phase flow of nitrogen.

2. Two-phase flow of nitrogen is similar to that of other, non-cryogenic, fluids; (e.g. water.

3. The quality of a fluid flowing in a pipeline is a primary parameter in the determination of two-phase pressure drop.
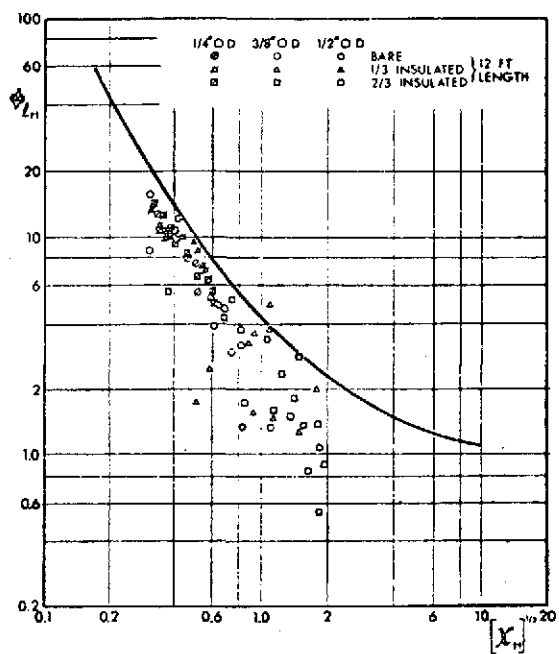
$$X_{tt} = \left(\frac{\rho_v}{\rho_\ell}\right)^{0.571} \left(\frac{\mu_\ell}{\mu_v}\right)^{0.143} \left(\frac{1}{X} - 1\right)$$

Figure 1. Comparison of Two-Phase (Diabatic) Pressure Drop Data of Liquid Nitrogen With Martinelli-Nelson Prediction

TRANSIENT FLOW OF CRYOGENIC FLUIDS
Steward, W.G., Colorado State University, PhD Thesis
68-14,951, 1968.

OBJECTIVE. - To develop an analytical method and a computer program to predict
the cooldown characteristics of cryogenic transfer lines.

PERTINENT WORK PERFORMED. - An analytical model was developed, a computer
program written ("COOLDOWN"), and an experimental program conducted. The
author discusses previous work done in the field with a number of references.
Transient flow tests were performed in LH_2 and LN_2 using 0.625 and 0.215 inside
diameter flow lines of various lengths. Length-to-diameter ratios investigated
ranged from 480 to 3840 (Figure 1). Tests were performed with the incoming liquid
either subcooled or saturated with respect to the pipe pressure. The computer
program uses short time steps initially to determine the magnitude and period of early
pressure and flow transients, and then longer time steps in a "quasi-steady" mode to
predict total cooldown times. The flow is assumed to be one-dimensional, the phases
are in thermal and mechanical equilibrium, there is no axial conduction along the
pipe, and there is no heat transfer from the external environment to the pipe.

MAJOR RESULTS. -

1. Initial line surges are considerably greater for subcooled liquid than for
    saturated liquid.

2. In the higher density LN_2, peak surge was larger and occurred later than in LH_2.

3. At lower pressures the computer program predicts peak surge levels reasonably
    well, but overpredicts as the critical pressure is approached (Figure 2).

4. Peak surges caused reverse flow rates ten times greater than the initial forward
    flow rate (Figure 3). Computer predicted peak flows were more accurate in
    the forward direction.

5. Cooldown of long pipelines is controlled primarily by restrictions to gas flow
    rather than by heat transfer.

6. Cooldown times are longer for saturated incoming fluid than for subcooled fluid,
    due to the large amount of vapor evolved.

7. Cooldown time is proportional to line length and inversely proportional to the
    inlet pressure (Figure 4).

8. Surging is aggravated by liquid subcooling, high liquid density, long transfer lines,
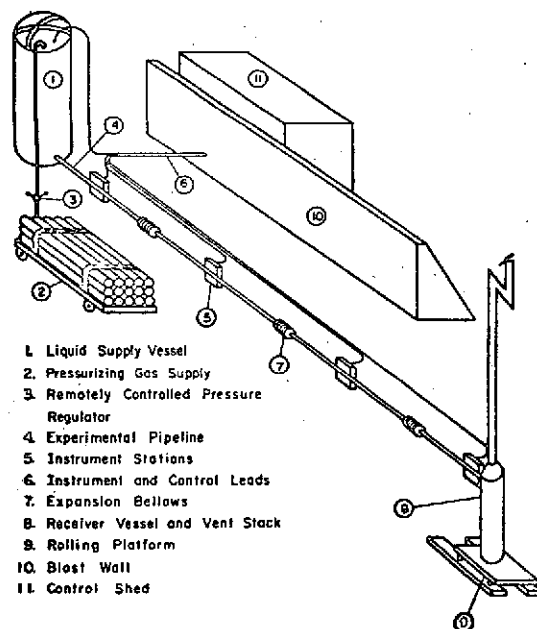   and rapid valve openings.

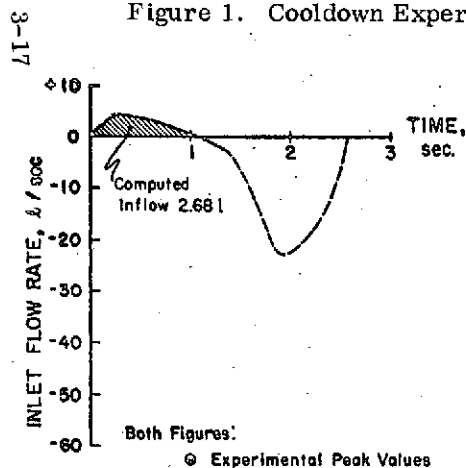Figure 1. Cooldown Experimental Facility

1. Liquid Supply Vessel
2. Pressurizing Gas Supply
3. Remotely Controlled Pressure Regulator
4. Experimental Pipeline
5. Instrument Stations
6. Instrument and Control Leads
7. Expansion Bellows
8. Receiver Vessel and Vent Stack
9. Rolling Platform
10. Blast Wall
11. Control Shed

All Figures: —— Experimental Runs
——— Computed with $T_{in} = 20.5°K$

| P_{in} = 2.52 atm.abs. or 25 psig. | 4.22 atm.abs. or 50 psig. | 5.92 atm.abs. or 75 psig. | 7.62 atm.abs. or 100 psig. | 9.32 atm.abs. or 125 psig | 11.0 atm.abs. or 150 psig. |

Figure 2. Subcooled Liquid Hydrogen Maximum Pressure Surge at Station 1 of Transfer Line A

Computed Inflow 2.681

Both Figures:
⊙ Experimental Peak Values

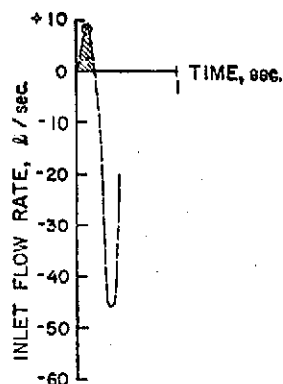Figure 3a. Typical Inlet Flow Surge for Subcooled Liquid Nitrogen. Transfer Line A, P_{in} = 75 psig.

Figure 3b. Typical Inlet Flow Surge for Subcooled Liquid Hydrogen. Transfer Line A, P_{in} = 75 psig.

⊙ 150 ft. Transfer Line B
△ 82 ft. Transfer Line C
▢ 25 ft. Transfer Line D
—— Computed by the Simplified Method Roughness of Drawn Tubing.
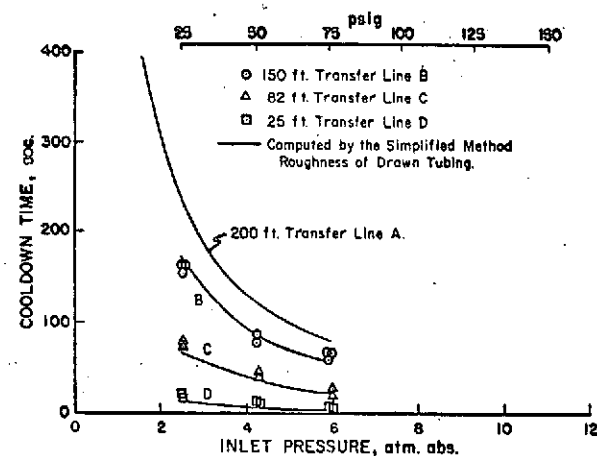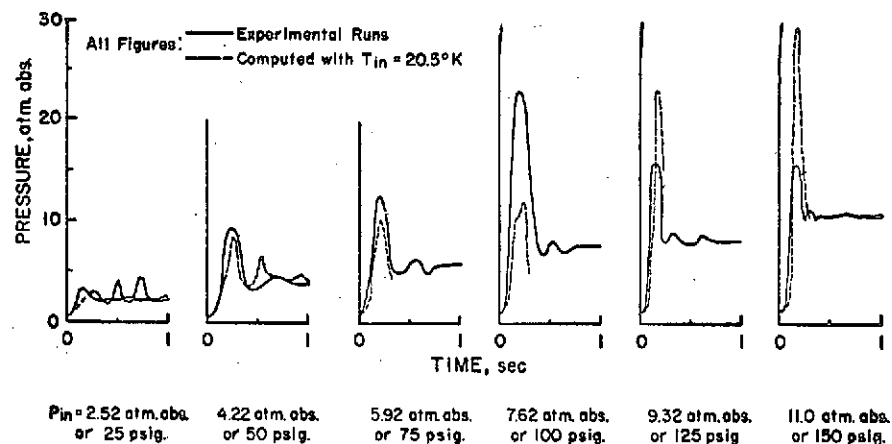
200 ft. Transfer Line A.

Figure 4. Cooldown Time for Subcooled Liquid Nitrogen Showing the Effect of Length

A STUDY OF COOLDOWN OF METALS, FLOW
INSTABILITY, AND HEAT TRANSFER IN TWO-PHASE
FLOW OF HYDROGEN, Manson, L., Miller, W. S.,
Rocketdyne, Research Report 68-40, NAS8-19, February, 1968

OBJECTIVE. - To provide information on transient, two-phase hydrogen chilldown
of both coated and uncoated transfer lines, and on flow instability and heat transfer
in two-phase flow.

PERTINENT WORK PERFORMED. - Five different metals were used to fabricate one-
foot long tubes with different heat contents (Table 1). Three tubes were subsequently
coated with 0.01-inch thick Kel-F trifluorochloroethylene on the inside diameter.
An equation was developed expressing coating thickness to reduce cooldown time as
a function of coating material thermal conductivity and average heat transfer coefficient
for the uncoated tube for (a) the entire cooldown and (b) the nucleate boiling portion
of the cooldown. Heat transfer and flow phenomena during cooldown of metal tubes in
two-phase hydrogen flow are closely coupled. Modifications of single-phase heat
transfer correlations to adapt them to two phase flow are not valid. Although
two-phase correlations yield reasonable results at the initiation of cooldown (high
wall temperatures), agreement in the low-wall-temperature region was not as good.
Experimental stability results obtained in this study were not predictable by existing
empirical correlations (Figure 1).

MAJOR RESULTS. -

1. Thin, insulating coatings will shorten cooldown times when the heat transfer
    coefficients in forced-convection film boiling are low relative to those in the
    nucleate boiling region (Figure 2).

2. Coatings can be used to reduce the rate of heat addition to a fast-moving hydrogen
    stream, and to promote flow stability.

3. To suppress flow instabilities in subcooled liquid, relatively high flow rates were
    required. Much lower flowrates were required for saturated fluid flow.

4. Stability maps (Figure 1) are restricted to the system investigated. System
    damping was high, making it difficult to define conditions which lead to instabilities.

Table 1. Tube Dimensions and Heat Content

Group		321 Steel	K Monel (29% Cu)	Titanium Alloy (5.3-% Al, 2.5-% tin)	Tens-50 Aluminum	Copper
GROUP I	OD/ID	.75/.50	.75/.50	.85/.50	.85/.50	.75/.50
Heat content between 500-50 R, Btu		27.9	29.7	29.1	30.6	30.0
between 220-50 R, Btu		5.0	5.4	6.3	6.7	6.5
GROUP II Same OD/ID as Group I						
Kel-F coated		X	X	None	None	X
GROUP III	OD/ID	.56/.50	.56/.50	.56/.50		
Heat content between 500-50 R, Btu		6.0	6.3	4.5	None	None
between 220-50 R, Btu		1.0	1.1	0.9		
GROUP IV	OD/ID	.36/.30	.36/.30			
Heat content between 500-50 R, Btu		3.3	3.6	None	None	None
between 220-50 R, Btu		0.6	0.6			

3-19
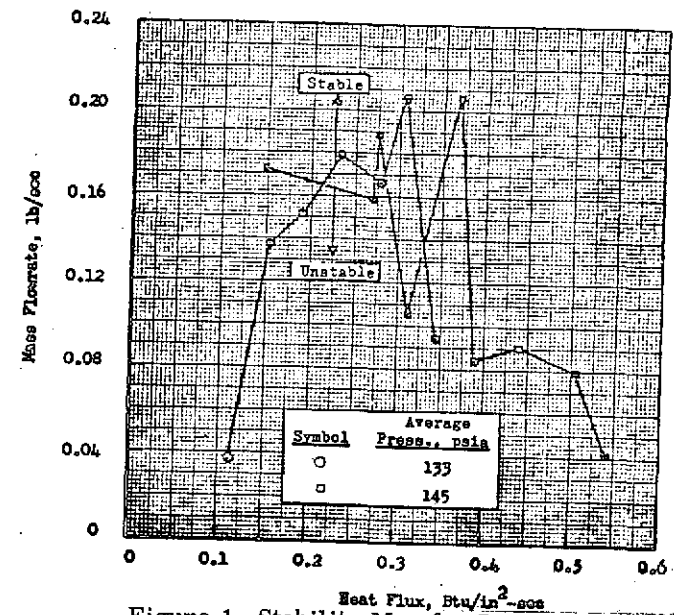
Figure 1. Stability Map for Low Pressure Hydrogen Experiments

Symbol	Average Press., psia
○	133
□	145

K Monel plates - Kel F coated

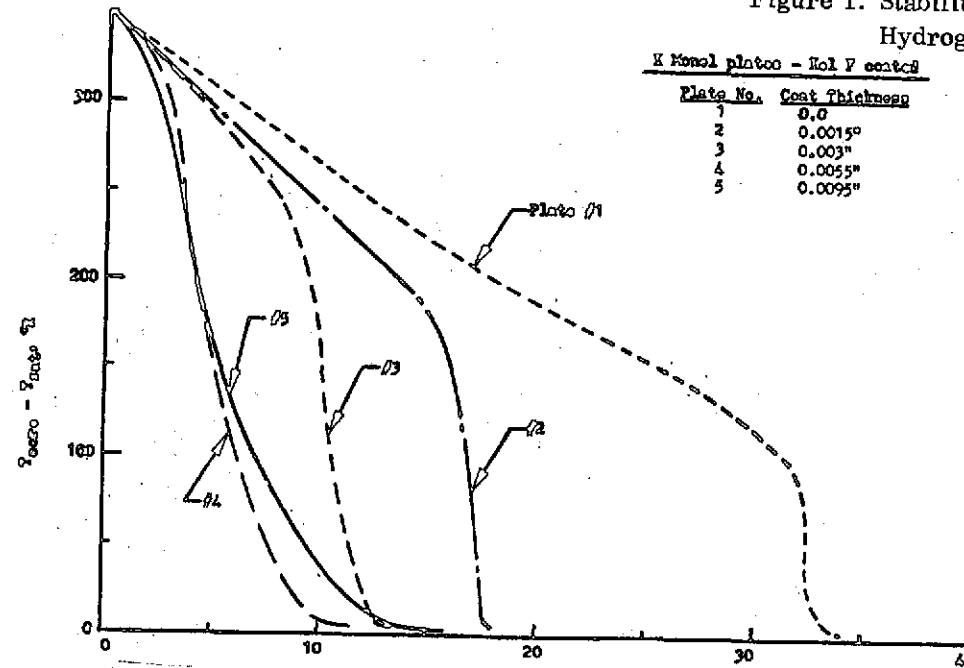| Plate No.	Coat Thickness
1	0.0
2	0.0015"
3	0.003"
4	0.0055"
5	0.0095"

Figure.2. Cooldown of Coated and Uncoated Vertical Plates In Saturated Liquid Nitrogen-Temperature vs Time

A STUDY OF CRYOGENIC CONTAINER THERMODYNAMICS
DURING PROPELLANT TRANSFER
Vernon, R.M., Brogan, J. J., LMSC K-14-67-3, NAS8-20362, Nov 1967.

OBJECTIVE. - Provide analytical and empirical descriptions of transient phenomena in cryogenic transfer lines during chilldown. Work was also accomplished on receiver tank filling, which is covered in another summary.

PERTINENT WORK PERFORMED. - Work consisted of both analysis (development of a computer model) and test to verify the model. Basic elements of the computer model are illustrated in Figure 1. Mass, momentum and energy balances are applied to the pipe wall and flowing fluid. Pipe fluid length is broken into as many as 200 nodes. The finite difference calculation procedure consists of assuming a steady flow rate, calculating fluid conditions down the line, comparing calculated exit pressure with receiver pressure, and adjusting the flow until agreement is reached. Wall temperatures are constant over each time step and are updated at the end of each time step based on the heat removed. Two-phase flow is assumed to be homogeneous, and boiling heat transfer is by superposition (forced convection heat transfer plus pool boiling per Breen and Westwater, 1962). Output data consist of line temperatures, fluid temperature, pressure, velocity and quality, and heat rates at each node as a function of time. Limitations are that line diameter and wall thickness are constant, line is perfectly insulated and flow is uniquely determined by specified inlet temperature and pressure and outlet pressure. The ability to handle choked flow for two phase as well as for vapor exit conditions was found to be important during testing and was added to the version used for line-receiver integration. Also, for this version, flow and pressure oscillations are calculated separately using a spring (gas)- mass (liquid) analogy. Correlations were made with test data from the present work (1/2-in. I.D. × 5/8-in. O.D. Cu., 28 ft and 17 ft vacuum jacketed lines with LN_2) and with NBS data (5/8-in. I.D. Cu., 200 ft vacuum jacketed line with LN_2 and LH_2). Typical data are presented in Figures 2, 3 and 4.

MAJOR RESULTS. -

1. Better agreement was obtained between measured wall temperature time histories for long lines (L/D >3800 for LH_2 and > 475 for LN_2) than short lines. As the L/D ratio is decreased, transient chilldown is increasingly dominated by pressure and flow surges in the fluid. Predictions of overall chilldown time were within ±15% of test data.

2. Agreement between predicted and measured frequency and magnitude of pressure and flow oscillation was generally between ±10%.

COMMENTS. - Substantiation of statement (2) was not obvious from data presented.
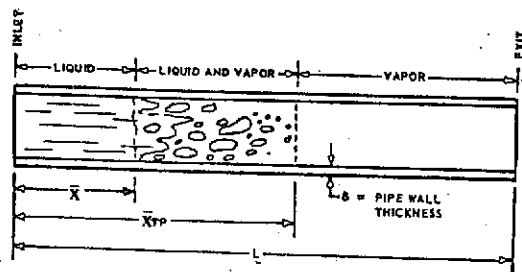
C_{p_w} = HEAT CAPACITY OF WALL

C_{p_g} = HEAT CAPACITY OF GAS AT CONSTANT PRESSURE

P_w = MASS DENSITY OF WALL

$\overline{v}_0$ = MASS RATE OF FLOW OF GAS

h_1' = HEAT-TRANSFER COEFFICIENT IN TWO-PHASE REGION

h_2' = HEAT-TRANSFER COEFFICIENT IN GAS REGION

T_0 = INITIAL WALL-TEMPERATURE DISTRIBUTION

t = TIME VARIABLE

z = LENGTH COORDINATE MEASURED FROM INLET OF PIPE

D = TUBE DIAMETER

T_s = SATURATION TEMPERATURE OF LIQUID HYDROGEN

Figure 1. Flow Model for Transfer Line
Chilldown Analysis

Figure 2. Line Temperature History with Subcooled Liquid Nitrogen
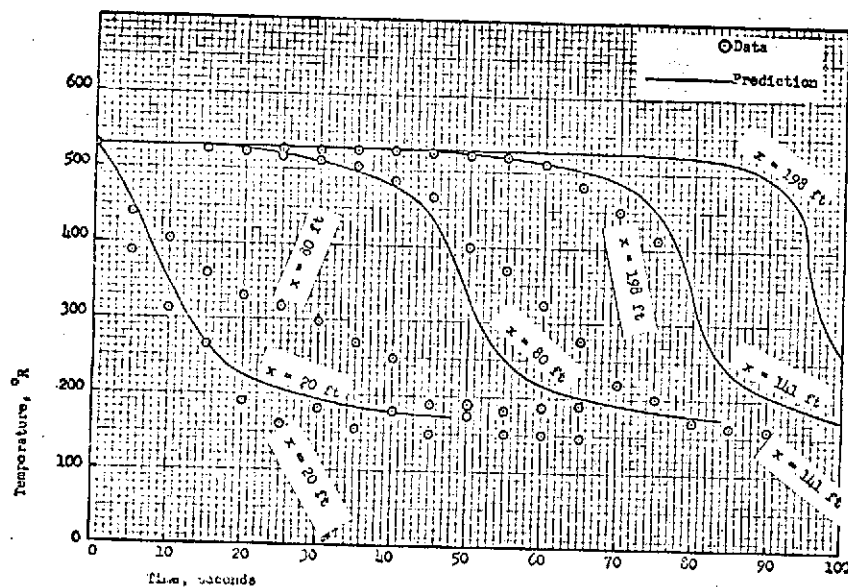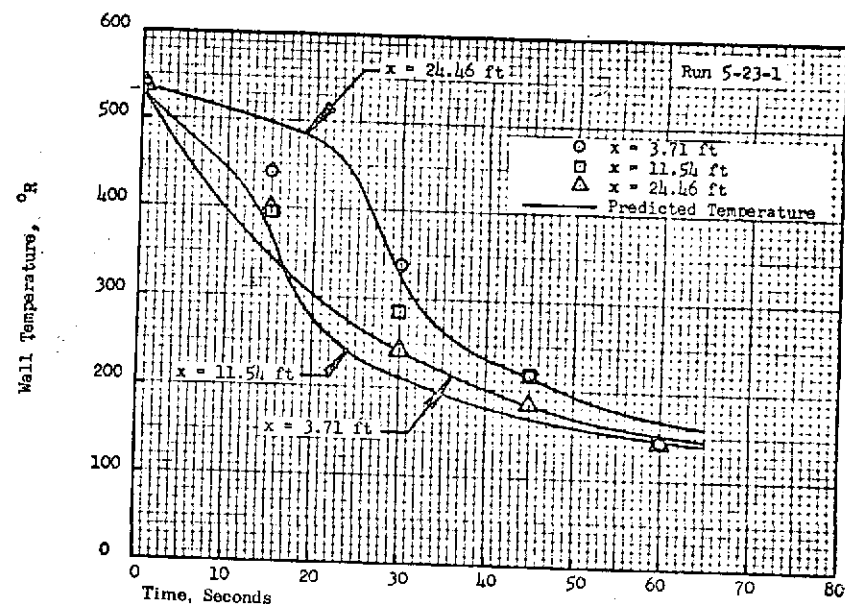at a Driving Pressure of 24. 8 psia

Figure 3. Comparison Between Computed and Measured Line Temperature
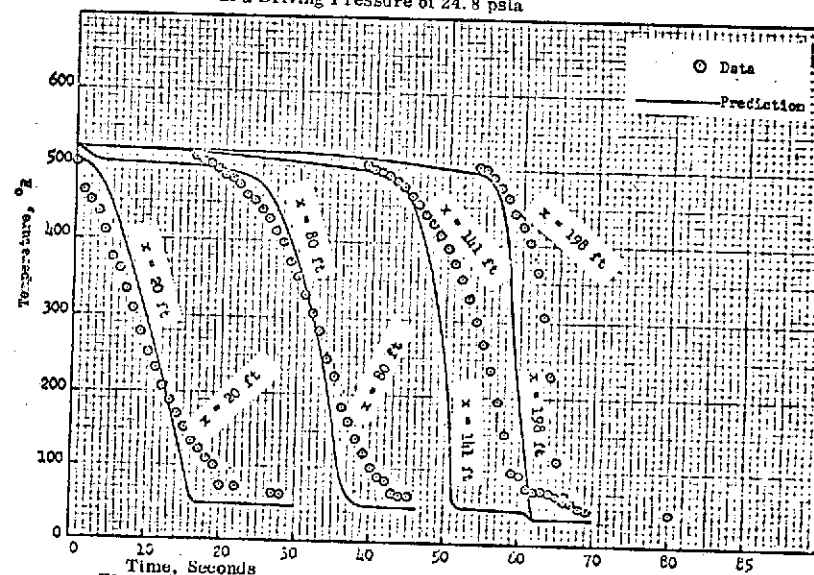Histories with Saturated Liquid Hydrogen at a Driving Pressure of
5. 1 atm.

Figure 4. Comparison Between Computed and Measured Line Temperature
Histories with Subcooled Liquid Hydrogen at a Driving Pressure
of 5. 1 atm.

BUOYANCY EFFECTS ON CRITICAL HEAT FLUX OF FORCED
CONVECTIVE BOILING IN VERTICAL FLOW
Papell, S. S., et al, NASA-LeRC, TN D-3672, October 1966

OBJECTIVE. - To determine the conditions under which buoyancy influences the critical heat flux level of a vertically-flowing, two-phase heat transfer system.

PERTINENT WORK PERFORMED. - Tests were performed in which LN_2 was flowed vertically through a resistance-heated, 0.505-in. inside diameter, 12-in. long steel tube. At a constant inlet pressure, power input to the heaters was gradually increased until the condition of criticality was established. Inlet pressures ranged from 50 to 240 psia, inlet velocities from 0.5 to 11.0 feet per second, and fluid subcooling from 12 to 51 Fahrenheit degrees. Each set of conditions was run both in the upward and downward directions to determine the effect of buoyancy on critical heat flux. Test data were plotted in the form of critical heat flux versus inlet velocity for upward and downward flow at a given inlet pressure (Figure 1). Below a certain velocity, approximately 7 ft/sec in Figure 1b, buoyancy affected the level of the critical heat flux. Above this point, the flow direction apparently had no effect. It was postulated that below the critical velocity, in the "buoyancy-dependent" zone (Figure 2) the flow may have been annular-dispersed, characterized by liquid droplets in a gaseous core surrounded by a liquid annulus on the tube wall. Above the critical velocity in the "buoyancy-independent" zone, the flow was said to change to bubbly or slug flow. No data are presented to support this flow regime identification.

MAJOR RESULTS. -

1. Under certain conditions, the critical heat flux level for upward flow is significantly higher than that for downward flow.

2. Buoyancy effects on critical heat flux increased with decreasing inlet pressure and subcooling, but decreased with increasing inlet velocity. Above certain velocities buoyancy effects were erased by fluid momentum.

3. For upward flow, with pressure above 150 psia, above an inlet velocity of 5 ft/sec, an increase of pressure increases the critical heat flux, while below 5 ft/sec there is a decrease in the critical heat flux with increased pressure.
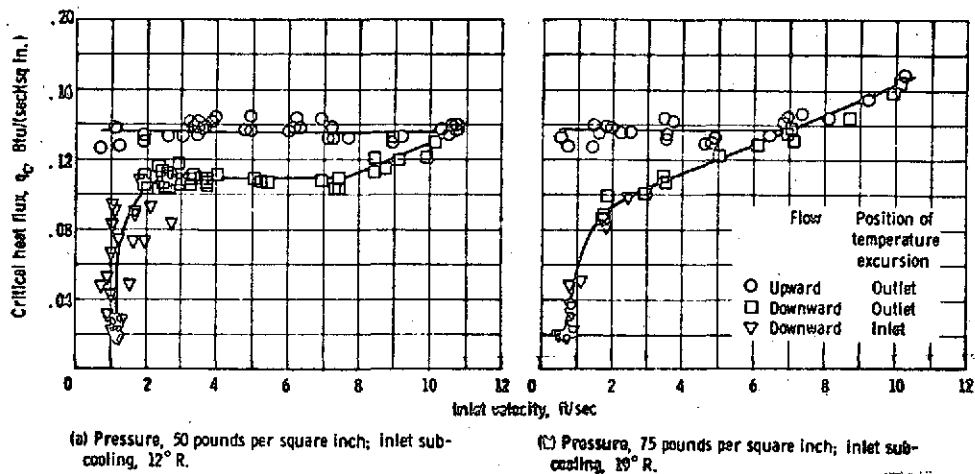
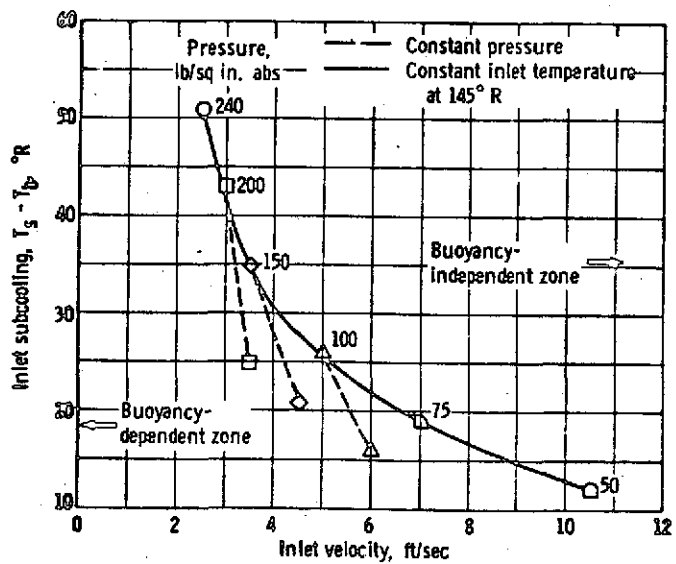Figure 1. Critical heat flux as function of inlet velocity for upward and downward flow of liquid nitrogen.

Figure 2. Susceptibility of liquid nitrogen flow system to buoyant effects on critical heat flux.

DIGITAL DISTRIBUTED PARAMETER MODEL FOR ANALYSIS
OF UNSTEADY FLOW IN LIQUID-FILLED LINES
Wood, D.J., et al; NASA-LeRC, TN D-2812, May 1965

OBJECTIVE. - To develop a numerical distributed-parameter solution for unsteady
flow in liquid systems that is in a form general enough to be applied to a variety of
system configurations.

PERTINENT WORK PERFORMED. A numerical solution of the momentum and
continuity equations is developed using an approach similar to that used in the method
of characteristics solution. This approach is termed the wave-plan solution.
Incremental pressure pulses are computed from incremental flow rate changes,
propagated through the system at sonic speed, and partially reflected and partially
transmitted at all geometrical and physical discontinuities in the fluid network. With
the wave-plan analysis; viscous friction effects are easily included, perturbing
functions of any form may be used, nonlinear relations are easily included, and both
transient and steady-state responses to disturbing functions are given. Digital
computer subroutines have been written for the most common types of discontinuities
which can then be combined to obtain models for various liquid flow systems. Sub-
routines representing a terminal flow orifice, an internal (friction) orifice, and a
diameter discontinuity are described in the appendices.

Two detailed examples are presented, showing responses of straight and tapered
lines to periodic sinusoidal flow disturbances. For the straight line example, com-
parison between analytical and available experimental data indicate very good agree-
ment between wave shapes and magnitudes. The tapered line, approximated by a
series of diameter discontinuities (Figure 1), exhibited large variations in resonant
frequency (Figure 2) with the line taper factor, δ ($\delta = 0$ for a straight tube). The
line taper factor is defined as one-half the difference between the line exit and entrance
diameters. This would indicate that some control could be exerted over the dynamic
response of a flow system by the judicious choice of tapers.

3-24
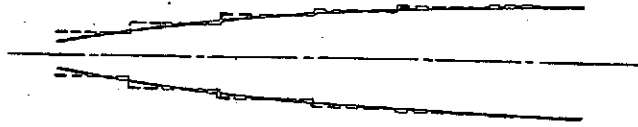
Step-diameter-change approximation to tapered line.
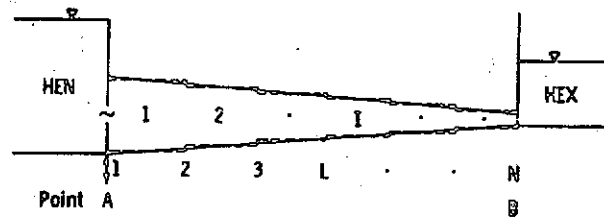
Reservoir conduit system with tapered line
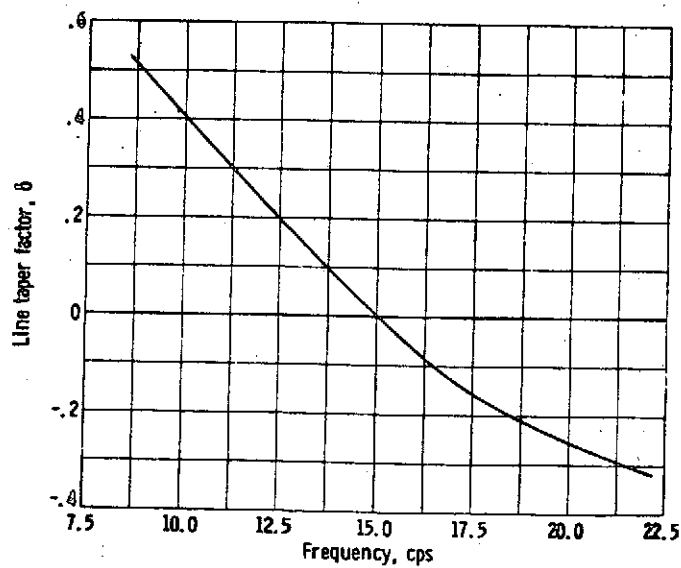
Figure 1. Tapered Line Model

Figure 2. Variation of Resonant Frequency
with Taper Factor

SOME IDEALIZED SOLUTIONS FOR CHOKING, TWO-PHASE
FLOW IN HYDROGEN, NITROGEN, AND OXYGEN
Smith, R.V., NBS, Advances in Cryogenic Engineering,
Vol. 8, August 1962

OBJECTIVE. - To develop analytical models for predicting the limiting flow rate of
two-phase, saturated hydrogen, nitrogen, and oxygen.

PERTINENT WORK PERFORMED. - Three models of saturated, two-phase fluid flow
were developed: (1) homogeneous, thermal equilibrium; (2) separated-phase, thermal
equilibrium, vapor-choking; and (3) homogeneous, metastable (phases homogeneous
but insufficient time to achieve thermal equilibrium). For the homogeneous model
the flow is assumed to be one-dimensional, horizontal, steady, and adiabatic. Model
(2) assumes the flow is choked when the velocity of the vapor phase as predicted by the
Martinelli-Nelson 1948 correlation reaches the sonic velocity for the vapor phase.
Based on the equations developed for model (1), curves of mass limiting flux are pre-
sented as a function of pressure and quality (vapor fraction) for H_2, N_2, and O_2.
An example for hydrogen is shown in Figure 1. In the development of model (3),
the additional assumptions of incompressible liquid and ideal gas were made, which,
particularly for H_2, limit the useful results to relatively low reduced (P/P critical)
pressures. The models were selected to bracket actual flow cases. A summary of
the available experimental, two-phase, choking studies up to 1962 are presented in
Figure 2 in the cross-hatched areas. Here the measured critical mass flux (flow
rate per unit area) ratioed to the flux predicted by the homogeneous thermal equilibrium
model (HO) is plotted against fluid quality. The idealized models were used to generate
the dotted curves shown in Figure 2.

MAJOR RESULTS. -

1. For low fluid qualities, the homogeneous, thermal equilibrium (1) and homogeneous,
    metastable (3) models tend to bracket the experimental data (Figure 2).

2. For higher qualities (>0.2), the separated-phase, thermal equilibrium model (2)
    predicts the experimental results with reasonable accuracy.

Subscripts: P_R = reduced pressure
             HO = homogeneous, thermal equilibrium
             MET = homogeneous metastable
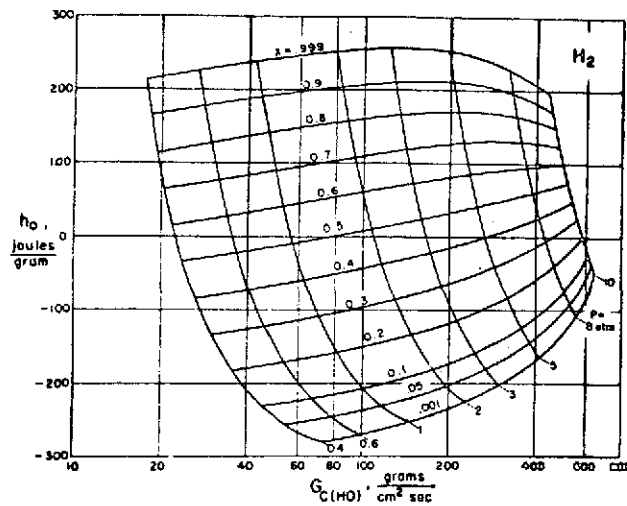
Figure 1. Mass limiting flow predictions at
           the point of choking for H_2; homo-
           geneous, thermal equilibrium model.

Subscripts: HO = homogeneous thermal equilibrium
             MET = homogeneous metastable

Figure 2. Comparison of experimental two-
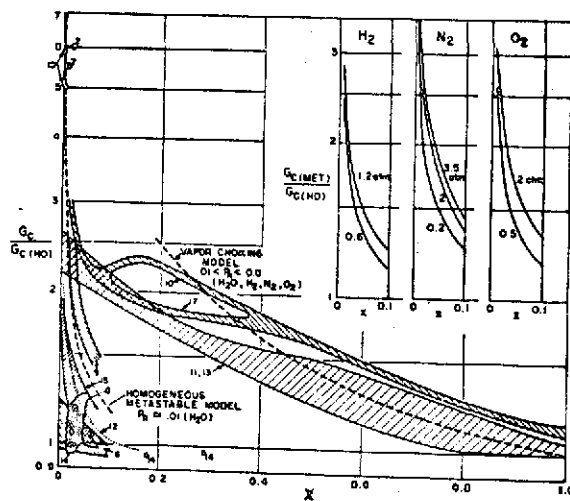   phase, choking studies with curves
           from the idealized solutions of
           this paper.

4.0 MASS GAUGING

Covering the various aspects of determining fluid quantity at low-g.

DEVELOPMENT OF A ZERO-G GAUGING SYSTEM
Bupp, F. E., TRW, AFRPL TR-74-5, Report No. 16740-6003-RU-00,
January 1974

OBJECTIVE. - Development of a practical, accurate method of gauging storable
propellants in zero-g environment using nucleonic techniques.

PERTINENT WORK PERFORMED. A nucleonic propellant gauging system has been
designed, fabricated and tested to meet the particular requirements of the Orbital Man-
euvering System (OMS). Pertinent design characteristics for this system are presented
in Table I. The nucleonic gauging system as designed consists of an array of gamma
ray emitting radio-isotope sources (Cs-137) and a corresponding array of cadmium
telluride (CdTe) radiation detectors along with peripheral electronics for signal con-
ditioning, input multiplexing, count accumulating, system processing (computer) and
display. Figure 1 shows a schematic of the complete experimental test arrangement.
Testing has been limited to the one "g" configuration, however analytical evaluations
have been performed projecting performance in the zero "g" condition on cylindrical
tanks with hemispherical ends and postulating predictable ullage geometry.

MAJOR RESULTS. -

1. Verification of system performance in a one "g" environment to a specified
   accuracy of ±0.5% over a range of 50% of total propellant capacity has been
   demonstrated.

2. Propellant gauging over the full-to-empty-tank conditions with a completely
   external system configuration has proven impractical because of required source
   energy limitations, dose rate, electronic speeds and dynamic range.

3. Propellant behavior in complex tanks featuring baffles, brackets, etc. would be
   unpredictable and would require system characterization through extensive
   investigation/calibrations.

Table I. Synthesis of a Nucleonic Zero-G Gauging System
for the OMS Tanks

|	
Total System Error	< 0.35 percent (all loadings up to 50 percent)
Response Time	30 seconds
Total System Weight (Includes Flight Processor/Display)	~20 pounds
Number of Source-Detector Pairs	4
Pair Positions	1 on tank axis (R = 0)
	3 at 120° (12.0 in. < R < 19.5 in.)
Source Type	Cs-137 (Custom Capsule)
Strength	1.4 Ci (MMH)
	6.5 Ci (N_2O_4)
Collimators (k = 0.01)	Depleted Uranium
Dose Rate (Average over hemispherical end at empty tank)	0.05 mr/hr (MMH)
	0.24 mr/hr (N_2O_4)
Signal Conditioning Electronics	
Nominal Maximum Speed	< 10^5 cps
Detector	CdTe (0.2 cm x 2.5 cm^2)
Input Stage	Charge Sensitive Preamplifier
Shaping Stages	Double Differention/Double Integration
Time Constant	0.25 µsec/Pole Zero Compensation
Amplifier Noise Characteristic (4 pf)	<8.6 kev FWHM
Discriminator	Fixed Window
Output Pulse	0.25 µsec/5 volt square
Interface Counter	21-stage binary; COS/MOS
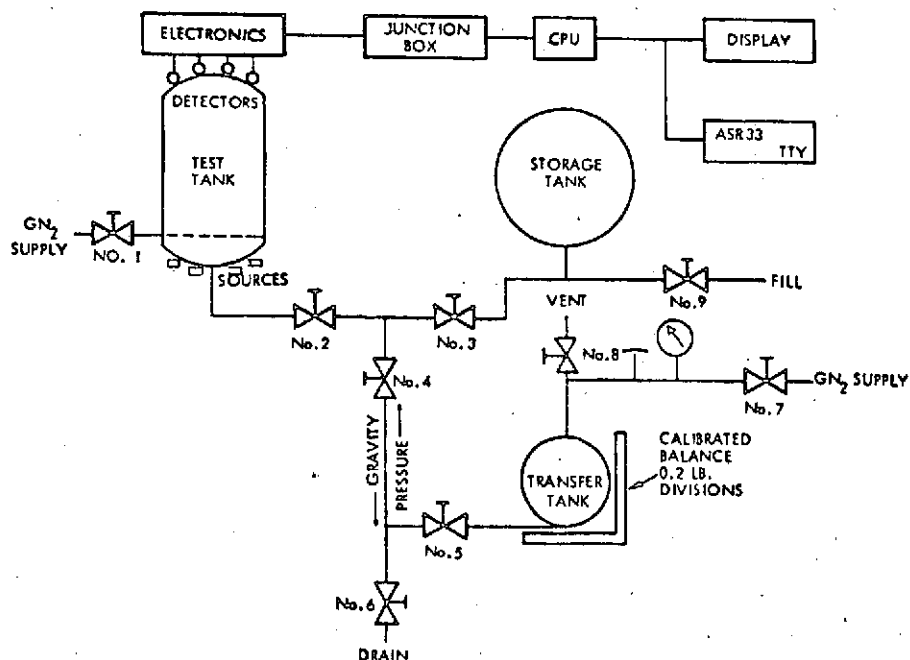
Figure 1. Experimental Arrangement: Nucleonic Gauging Tests

DEVELOPMENT OF ISOTHERMAL RIGS, FINAL REPORT
Kaminskas, R. A., Malone, D. J., TRW, NASA CR-124314,
NAS8-28574, April 1973

OBJECTIVE. - To design a Resonant Infrasonic Gauging System (RIGS), to fabricate same and perform an evaluation test program.

PERTINENT WORK PERFORMED. - A resonant infrasonic gauging system has been designed based on analytical and breadboard work performed in connection with possible use of such a system on the Apollo SPS tanks. Two prototype sensor (driver and follower piston) designs were fabricated. These units were adapted to perform on a 30-gallon tank and on a 100-gallon tank. A complementary electronic control system was designed and fabricated which provided drive, frequency and phase control to the bellows drive motor. The resonant frequency of the RIGS system is related to the ullage volume, and hence to the propellant volume, by the following equation:

$$f_r = \frac{1}{2} \sqrt{\frac{A^2 \gamma\, Pu}{M\, V_u} + \frac{K_B}{M}}$$

where: f_r = resonant frequency
  A = area of piston
  γ = ratio of specific heats of the ullage gases
  Pu = system static pressure

  K_B = spring constant of the bellows
  M = mass of the piston
  V_u = ullage volume

A test program has been performed with the following objectives: (1) evaluate in general the accuracy with which the system operates as a propellant gauging system, (2) determine the effect of ullage gases specific heats on system accuracy, and (3) determine the effect of surface tension screens upon the accuracy of the RIGS system.

MAJOR RESULTS. -

1. Test results of performance of the system are shown in Figure 1, which displays system resonant frequency vs. tank fluid in gallons.

2. The low resonant frequency of these systems require exceedingly low bellows spring constants. This presents difficult design problems which can only be overcome by electronic augmentation which simulates added mass and permits higher (practical) values of spring constants.

3. The existing designs are too slow for following transient conditions. This too, can be overcome by suitable redesigns of the electronic control system.

4. The system was found to operate in essentially the isothermal mode with errors due to specific heat ratios held to less than 1.0%.
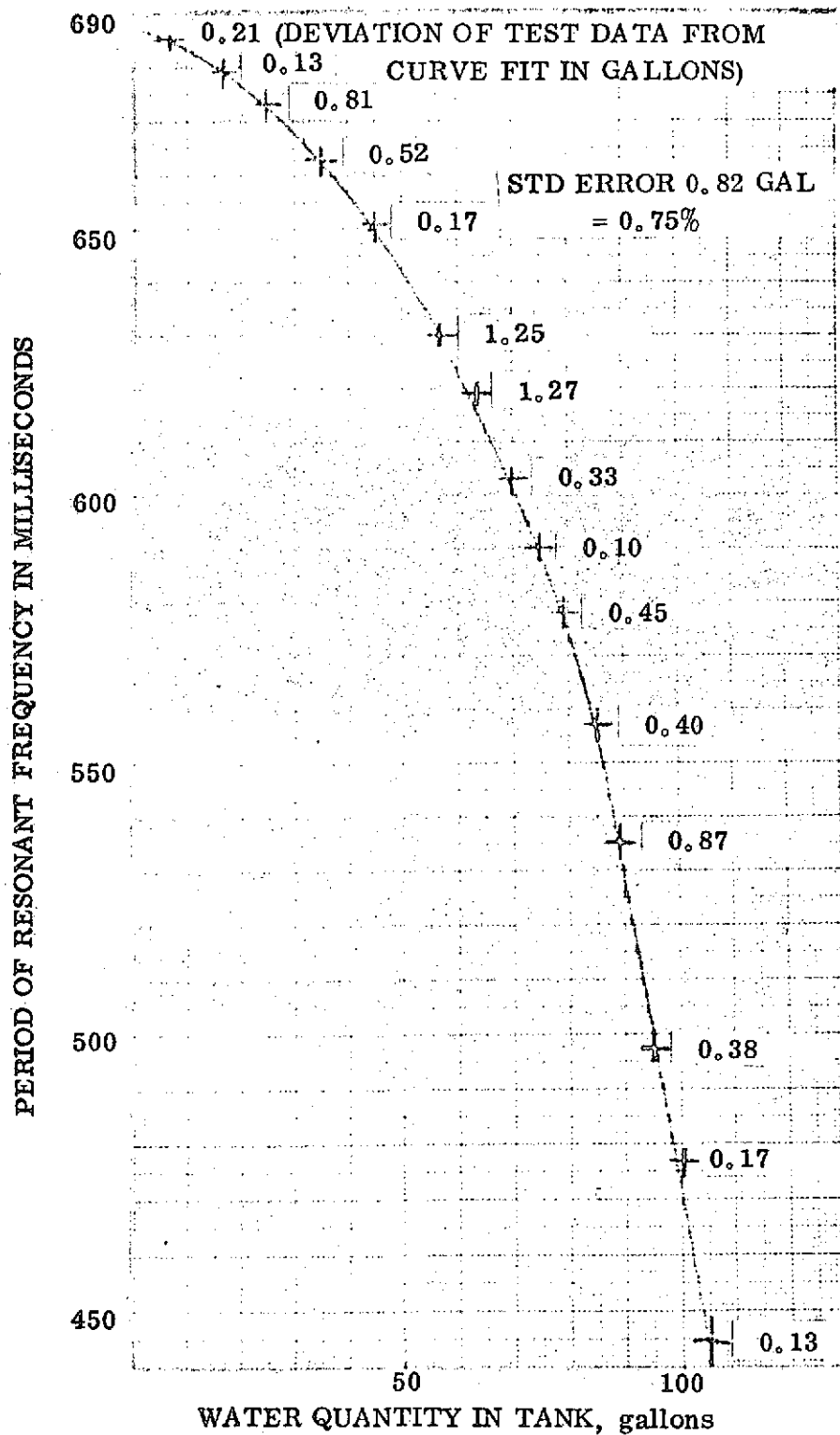
Figure 1. RIGS Test Data

DESIGN, DEVELOPMENT AND MANUFACTURE OF A
BREADBOARD RADIO FREQUENCY MASS GAUGING SYSTEM
Anon., Bendix Corp., Pub. No. 4879A-71, NAS8-30160,
January 1972

OBJECTIVE. - Build and deliver two breadboard RF Gauging Systems for gauging a
full-scale and a one-tenth-scale S-IVB tank. To test and evaluate these systems,
and, from empirical and analytical data results, develop scaling law determinations
and methods for determining system error.

PERTINENT WORK PERFORMED. - Two complete breadboard RF gauging systems
have been designed and fabricated along with scaled tanks for testing and evaluation.
Criteria have been established for optimizing operational frequency bands as a func-
tion of tank parameters and propellant dielectrics. Several types of RF tank probes
have been investigated with the result that the spiral antenna configuration was chosen
as providing best overall gauging results. Tank configuration, structural materials,
linings, and perturbations have been studied relative to their effect upon the tank quantity
factor (Q). System electronics, including RF sources, RF isolators, mode detection,
mode processor and output methods have been designed and refined to a reliable oper-
able system. The mathematical model for RF gauging developed under NAS8-18039
has been further refined to make it more responsive to various input parameters, such
as tank Q, dielectric properties and internal tank perturbations.

Testing and evaluation to investigate the feasibility of the system have been performed
in the following areas: (1) propellant loading, (2) bubbling and sloshing effects, (3)
propellant type vs. optimum frequency band, (4) tank/propellant orientation, (5) tank
configuration/perturbation effects, and (6) LO_2, LN_2 and LH_2 testing.

Follow-on progress reports published since this report cover extensive data
reduction and analysis efforts.

MAJOR RESULTS. -

1. The tests performed using the RF gauging system as developed and fabricated have
   demonstrated that RF gauging is a feasible and practical approach to propellant
   gauging in spacecraft.

2. Significant progress was made in system implementation, including RF probe
   design and electronic mode processing.

3. In-depth understanding has evolved regarding system implementation and gauging
   system interface with tank configuration variables.

4. Experimental data has lead to an updating of the mathematical model that improves
   response correlation of experimental and theoretical results.

5. Results of LH_2 testing indicate that the gauge shows promise of high accuracy, as
   concluded from dynamic test data, and that it is rapidly approaching the test equipment
   accuracies.

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PROPELLANT QUANTITY GAUGING SYSTEM UNDER
ZERO-G, Anon., TRW, NAS8-26116, August 1971

OBJECTIVE. - To summarize the results of a study evaluating several candidate pro-
pellant gauging systems suitable for use on the Space Shuttle vehicle, with the excep-
tion of the radio frequency gauge approach.

PERTINENT WORK PERFORMED. - The problems presented by zero g on the Space
Shuttle vehicle have been delineated and reviewed. The desirability of effecting pro-
pellant settling prior to gauging has been established and means for effecting this have
been reviewed. The following types of gauging have been reviewed and evaluated;
Gamma Ray attenuation, Resonant Infrasonic Gauging (RIGS), Ultrasonic Devices,
Ultrasonic Probe, Light Attenuation, Titration (Radioactive and Inert Gas) and Capaci-
tive gauging. In each case the operating principle is reviewed, applicability, and
performance limitations are detailed and a summary evaluation of the method is pre-
sented. Acoustic pumping and destratification by spraying techniques for propellant
positioning for simplifying propellant gauging are also reviewed.

MAJOR RESULTS. -

1. Ultrasonic methods appear possible but would require extensive development and
   testing to establish feasibility.

2. Light attenuating, titration, radio active traces, inert gases, and capacitance
   gauging are not considered as possible gauging systems for the Space Shuttle.

3. Table 1 tabulates the only practical ways of gauging LH_2 in zero-g conditions.
   Only nuclear, infrasonic and RF gauging are considered as being viable approaches.

4. If propellant settling techniques are employed, capacitance or ultrasonic means
   could be used. Also, liquid settling would simplify the nuclear gauge approach by
   reducing the number of source-detector pairs required.

Table 1.   Summary of Gauging System Application

	True Zero-g	Propellant Settling
LH$_2$ Tanks		
Tank without Screens	Nuclear (RF) *	Nuclear (RF) Level Measurement
Tank with Screens	Nuclear	Nuclear Level Measurement
LO$_2$ Tanks		
Tank without Screens	Nuclear RIGS (RF?)	Nuclear RIGS Level Measurement (RF?)
Tank with Screens	Nuclear RIGS	Nuclear RIGS Level Measurement

* Radio Frequency (RF) gauging was included only on the basis of other work.

MOL PROPELLANT GAUGING SYSTEM
Bliss, J., MACDAC, DAC-63140,
Proceedings of Low-G Seminar, May 1969

OBJECTIVE. - To provide a propellant gauging system for the Manned Orbital Lab-
oratory (MOL) to insure conservation of sufficient propellant for de-orbit. To meet
this requirement a pressure volume temperature (PVT) gauging concept is used.

PERTINENT WORK PERFORMED. - The system consists essentially of propellant
tanks featuring bladder propellant control and high pressure helium tanks. Both tanks
are instrumented for measurement of pressure and temperature. Figure 1 shows the
general arrangement of the system and Figure 2 shows the propellant gauging assembly
schematic.

Performance of the system is predicated upon calculating changes in the pressurant
remaining in the high pressure helium bottle based upon its monitored pressure and
temperature. The mass of helium in the propellant tank ullage bladder is equal to the
mass that has left the high pressure bottle. Measurement of pressure and temperature
in the pressure tank ullage together with calculated mass and estimated ullage com-
position is used to calculate a change in ullage volume. Measurement of propellant
temperature allows conversion to propellant mass.

MAJOR RESULTS. -

1. The basic elements and operating principles of PVT propellant gauging concept are
   presented with an outline of its successful application to the MOL spacecraft.

2. Figure 3 is a block diagram of the Gauging Program for a single system. In addi-
   tion to the gauging function, provision is made for leak detection self check.

COMMENTS. - Application of this system to significantly larger propellant volumes/
masses poses problems which makes this approach to propellant gauging look very
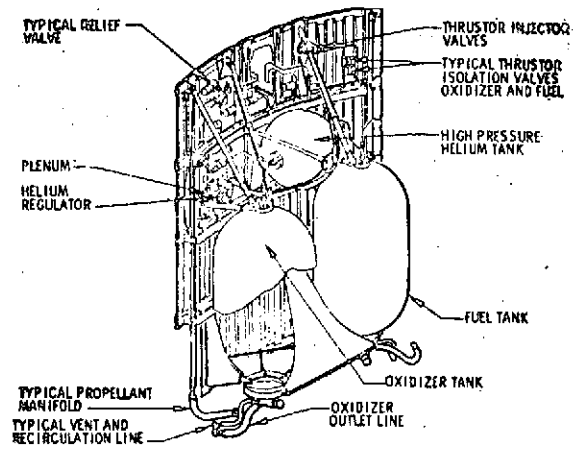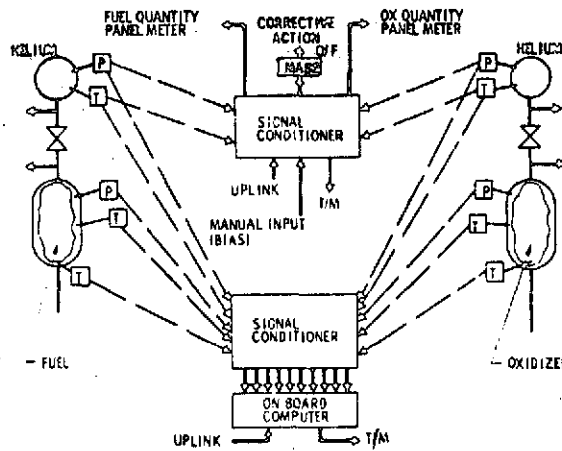questionable.

Figure 1. Propellant Systems-Gen. Arrangement

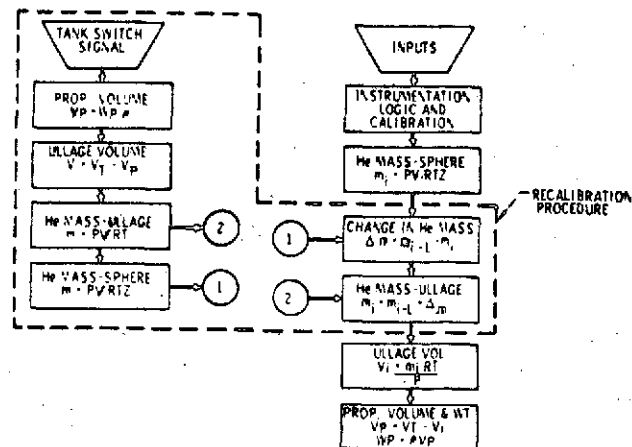
Figure 2. Propellant Gauging Assembly

Figure 3. Gauging Program

SUBCRITICAL CRYOGENIC STORAGE DEVELOPMENT
AND FLIGHT TEST
Allgeier, R. K., NASA-JSC, TN D-4293, February 1968

OBJECTIVE. - To design and fabricate operational subcritical cryogenic storage
systems for ground test (Phase I), and to evaluate the performance of follow-on sub-
critical hardware in earth orbit (Phase II).

PERTINENT WORK PERFORMED. - Operational concepts for the storage of sub-
critical cryogenic fluids and the delivery of single-phase (vapor) were developed.
During Phase I two subcritical systems were fabricated by AiResearch and tested
which employed regenerative heat exchangers for pressure control and electrical
heaters for rapid depletion. A capacitance gage matrix was installed in the tanks for
fluid quantity measurements. Thermodynamic and vibration tests of the Phase I
devices indicated that the concept warranted verification in a low-gravity environment.

The Phase II subcritical storage and supply system (Figure 1) was a self-contained
package having all components necessary to store liquid nitrogen for extended periods
and deliver the vapor phase under the environmental conditions of orbital flight. The
tank was a spherical dewar on the order of 25 inches inside diameter. Two systems
were fabricated, one for orbital evaluation and the other for qualification testing and
flight system backup. An electrical heater was used to replace the regenerative heat
exchangers to minimize system complexity. The system was flown aboard Apollo
Mission AS-203 in July 1966. It exhibited good pressure control and stability, and the
heat exchanger outlet temperature and the delivery temperatures were significantly
above saturation. The capacitance gage successfully monitored the quantity of fluid
in the tank throughout the test.

MAJOR RESULTS. -

1. A flightweight, subcritical cryogenic storage system was designed, fabricated
    and successfully tested in earth orbit.

2. This was the first successful orbital test of a three-dimensional wire matrix
    mass gaging device.

3. Single-phase vapor was consistently delivered by the system throughout the test.

Figure 1. Phase II Subcritical Nitrogen System

Design parameters			
Operating pressure range	130 - 170 psia	Ambient temperature range	-65 to + 160 °F
Delivery pressure	60 ± 5 psia	Delivery rate	1.25 ± .13 lb/hr
Relief pressure	220 ± 20 psia	Total electrical power available, prelaunch	28 V dc, 400W
Proof pressure	360 psia minimum		
Burst pressure	480 psia minimum	Total electrical power available, postlaunch	28 V dc, 174W
Maximum filled weight	275 lb		
Liquid nitrogen capacity	128 lb	Shelf life	1 year
Standby time, nonvented, at 160°F	30 hr	Radio noise specification	MIL-I-26600 (USAF)

5.0 OTHER INSTRUMENTATION

Covering liquid/vapor sensing at low-g, flowmetering, two-phase
flow quality gauging and temperature and acceleration measurement.

ASRDI OXYGEN, TECHNOLOGY REVIEW, VOLUME VI,
FLOW MEASUREMENT INSTRUMENTATION
Mann, Douglas B., NBS, NASA SP-3084, 1974

OBJECTIVE. - To survey the literature on cryogenic flowmetering to establish the
state-of-the-art of oxygen flowmetering in liquid and gaseous states.

PERTINENT WORK PERFORMED. - A comprehensive summary of information avail-
able on liquid and gaseous oxygen flowmetering was made along with an evaluation
analysis of commercial meters. Design information and performance characteristics
have been presented for the following types of flowmeters: Screw Impeller Volumetric
Flowmeter, Rotating Vane Volumetric Flowmeter, Oscillating Piston Meter, Head
Meters and Orifice Meters. In addition, information on the following types of flow-
meters is also presented: Angular Momentum Type, Turbine, and Vortex Shedding.
For each type of meter the principle of measurement is presented, along with design
and analysis data supported by operational characteristics and tabulated performance
summaries. Each flowmeter review is followed by a summary and conclusions.

MAJOR RESULTS. -

1. A graphic presentation of the flow ranges of the various types of cryogenic flow-
   meters is shown in Figure 1. Figure 2 presents the (3σ) precision characteristics
   of the flowmeter types shown in Figure 1.

2. Analysis shows that the existing state-of-the-art for oxygen service leaves a great
   deal to be desired when measurements must be made to a total uncertainty of less
   than ±2.0%.

3. A serious problem exists in the use of surrogate fluids in establishing performance
   and calibration data. The science of surrogate system applications has not been
   developed to a point where such substitutions can be made without introducing sig-
   nificant errors.

4. Prevailing problems associated with measurement of cryogenic oxygen flow are as
   follows:

   a. Lack of Standardization and interlaboratory comparison of existing reference
      facilities.

   b. Technology deficiency regarding surrogate test/calibration errors.

   c. The need for large flow reference systems to support present and future needs.

COMMENTS. - A supplemental report covering other flowmeter types is: An
Evaluation of Selected Angular Momentum, Vortex Shedding and Orifice Cryogenic
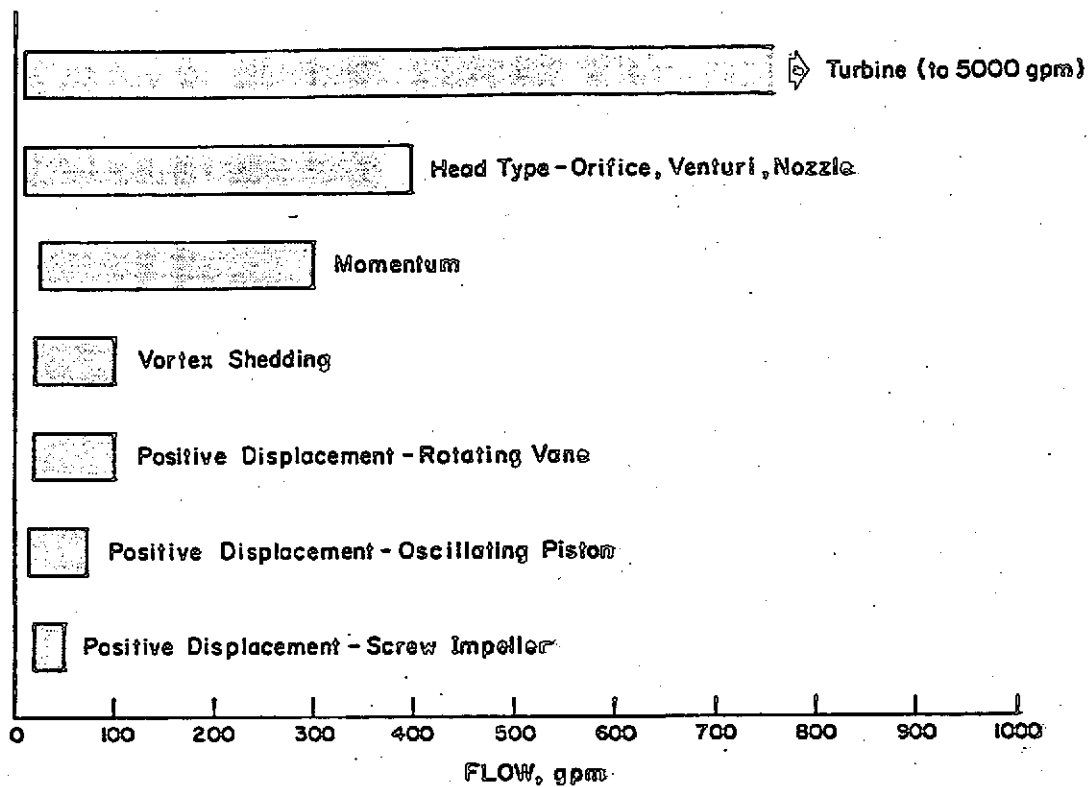Flowmeters by J. A. Brennan, et al, 1974, (NBS Technical Note 650).

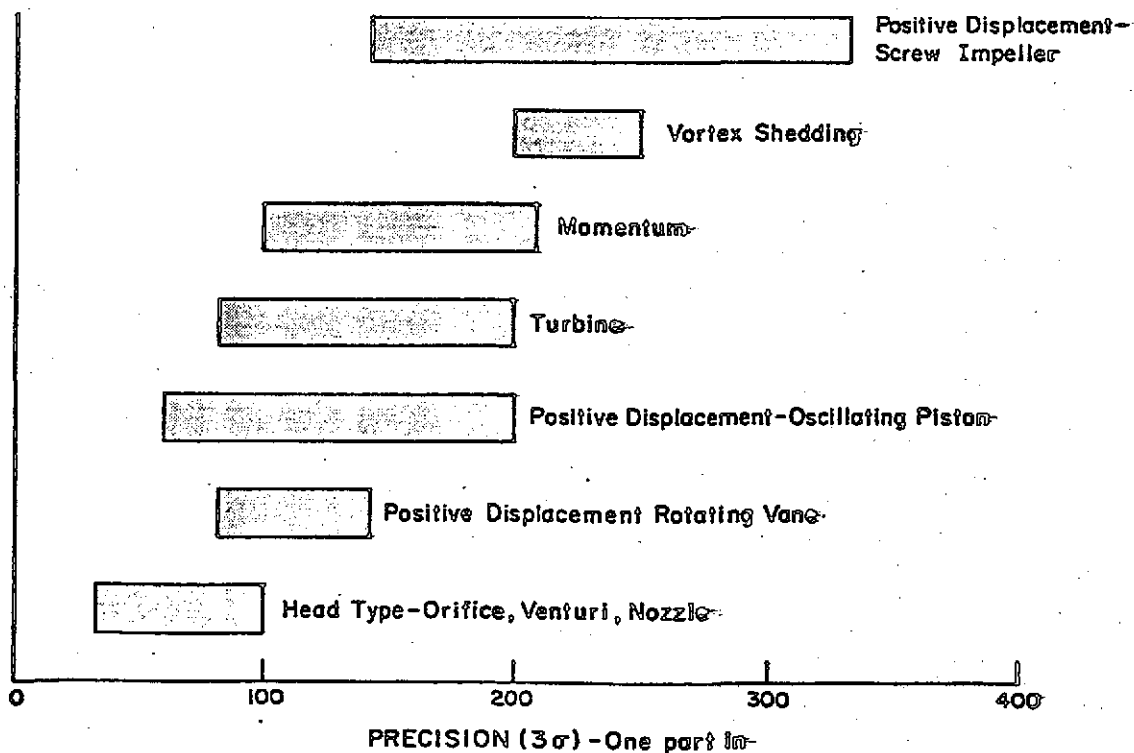Figure 1. Flow Ranges of Cryogenic Meters-Experimental Data from the Literature

Figure 2. Precision of Cryogenic Flowmeters-Experimental Data from the Literature

ASRDI OXYGEN TECHNOLOGY SURVEY, VOL. IV,
LOW TEMPERATURE MEASUREMENT
Sparks, L. L., NBS, NASA SP-3073, 1974

OBJECTIVE. - To summarize the current state of the art in cryogenic temperature
measurements at liquid oxygen temperatures and to summarize performance charac-
teristics of resistance thermometers, thermocouples and filled systems types.

PERTINENT WORK PERFORMED. - An excellent summary has been made of the state
of the art of cryogenic thermometry in the range of liquid oxygen, nitrogen and hydro-
gen temperatures. An overview of the International Practical Temperature Scale
(IPTS-68) relative to both older and contemporary temperature scales is presented
along with operational graphs. Techniques of low temperature thermometry are re-
viewed, including problems of thermal conduction and thermo electric error sources.
Basic design considerations and performance characteristics of the following types of
thermometers are presented; resistance (metals and non-metals), platinum, indium,
copper, carbon, and germanium. Also covered are the various types of thermocouples,
vapor pressure thermometers and gas thermometers.

MAJOR RESULTS. -

1. Figure 1 is presented as a summary of the principal instruments that can be effec-
   tively used between the temperatures of 4° and 300°K.

2. Figure 2 presents absolute temperature coefficient of resistance versus tempera-
   ture for several types of resistance thermometers and also one junction diode.

3. Indium exhibits all the desirable characteristics required of a resistance thermom-
   eter element for cryogenic ranges. It is recommended that the anisothropic be-
   havior of indium be studied with the purpose of constructing reproducible thermom-
   eters for which Cragoe Z functions might allow precise resistance temperature
   from only a few calibration points.

4. The very desirable characteristics of fast response time, size, ruggedness and
   high sensitivity, warrent needed development of the thin film carbon type thermom-
   eters. These units require further studies to understand their transport properties
   and to standardize methods of deposition of materials and substrates.
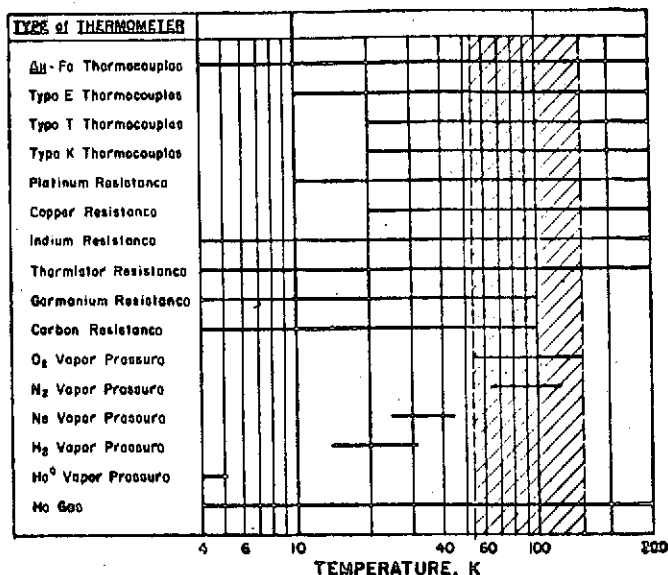
Figure 1. Graphic Summary of the Approximate Range of Use of Several Temperature Transducers Between 4 and 300K. The Shaded Area Represents the Temperature Range Between the Triple Point and Critical Point of Oxygen.
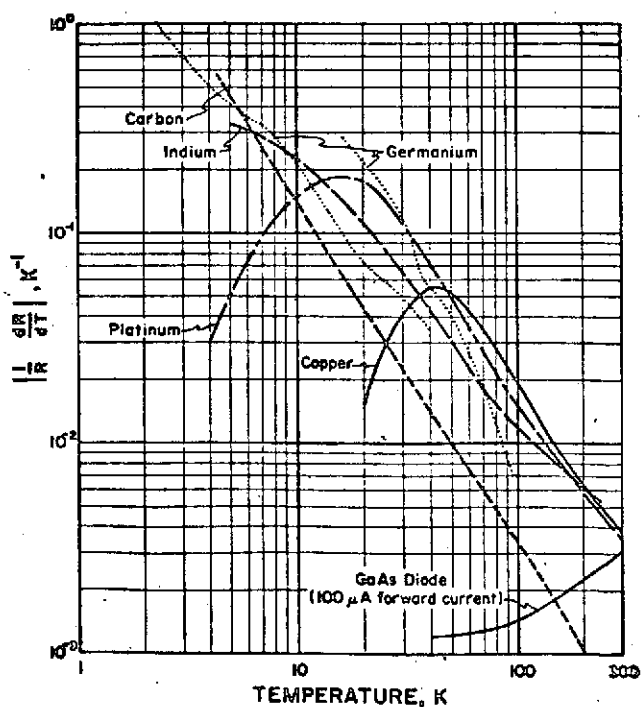

Figure 2. Comparaitve Absolute Values of the Temperature Coefficient of Resistance (K^{-1}) Versus Temperature (K) for Several Resistance Thermometers and one Junction Diode.

AN EVALUATION OF SEVERAL CRYOGENIC TURBINE FLOWMETERS.

Brennan, J.A., et al, NBS TN-624, October 1972.

OBJECTIVE. - To conduct performance evaluation tests on each of several types of volumetric and mass cryogenic turbine type flowmeters to determine their performance, accuracy, rangeability, long term stability, and boundary operational characteristics.

PERTINENT WORK PERFORMED. - Tests were performed utilizing the new NBS cryogenic flow facility which provides for dynamic gravimetric measurement of liquid nitrogen flow. Accuracy of mass flow measurement is estimated as being ±0.18%. Eight flowmeters representing five manufacturers were tested. Five were turbine type standard volumetric meters and three were volumetric meters combined with a compensation device that measured or inferred the fluid density whereby the volumetric output from the turbine meter was converted to mass output.

The performance of the flowmeters in liquid nitrogen is evaluated by reporting the precision and bias of the meters before and after an 80-hour stability test and by defining the extent of temperature, pressure, flow rate, subcooling, and time order (wear) dependencies. Meters were evaluated at flow rates from 20 to 210 gallons per minute, pressures from 32 to 112 Psia and temperatures from 72° to 90°K. Flow meter performance was plotted relative to the 1972 Conference on Weights and Measures tentative code for Cryogenic Liquid Measuring Devices which specified a maintenance tolerance of + 2% and -4%. The deviation was calculated from the vendors "K" factor supplied with the meter. The reported bias on each meter was obtained by evaluating the mathematical model at rated maximum flow rate at 80°K. The mathematical model used is: $y = \mu + aT + bT^2 + c\dot{m} + d\dot{m}^2 + e\theta$, where; y = Bias in %, μ = constant, T = Temperature, $\dot{m}$ = mass flow rate in lbs/sec, and θ = time order term. The coefficients a, b, c, d and e give an indication of the dependency of the corresponding terms and were reported for each rangeability test when significant.

MAJOR RESULTS. - Table 1 is a summary of the test results showing the performance of the eight turbine flowmeters. As a result of these tests:

1. All meters showed good bias stability but somewhat large bias values at the start of tests.
2. The precision (3 σ) values were good with the exception of the Type Z meter.
3. Some of the meters showed statistically detectable temperature and flow rate dependencies.
4. All meters showed a trend to overregistration and a loss of precision with subcooling.
5. Turbines were sensitive to overspeeding during cooldown which could result in bearing damage.
6. K factors were found to be a function of the cryogen in which the meters are operated. For maximum accuracy they must be individually calibrated in the fluid in which they will be used.

Table 1. Turbine Meter Performance Summary

Meter Identification	N (Volume Basis)	O	P	Q	R	S	V (Volume Basis)	Z (Mass Basis)	Z (Volume Basis)
Precision (3σ) at start, %	±0.69	±0.84	±0.54	±0.57	±1.02	±0.78	±1.11	±1.80	±0.57
Precision (3σ) at end, %	±0.66	-	±0.48	-	-	-	-	±2.40	±0.87
Bias at start, %	+3.82	+2.20	+0.10	+1.30	+1.93	+1.59	+0.42	+0.83	+1.08
Bias at end, %	+3.85	-	+0.09	-	-	-	-	-0.64	+1.23
Liquid Volume Metered During Stability Test	384,000 gal. (1,453,600 ℓ)	-	810,000 gal. (3,066,200 ℓ)	-	280,000 gal. * (1,059,900 ℓ)	-	-	-	624,000 gal. (2,362,100 ℓ)
Max. Test Flow Rate	80 gpm (5ℓ/s)	80 gpm (5ℓ/s)	180 gpm (11.3ℓ/s)	180 gpm (11.3ℓ/s)	120 gpm (7.6ℓ/s)	120 gpm (7.6ℓ/s)	225 gpm (14.2ℓ/s)	14.5 lbs/s (6.6kg/s)	130 gpm (8.2ℓ/s)
Minimum Subcooling, K	6	-	14	-	20	-	-	-	16
Operating Principle	Compensated Turbine	Turbine					Turbine	Compensated Turbine	
Size, in. (cm)	1-1/4 (3.2)	1-1/2 (3.81)				1-1/2 (3.81)	2 (5.08)	1-1/2 (3.81)	

NOTE: This table is a highly condensed summary of the results of an extensive testing program. In this table it has not been possible to present some information that may be important in some applications. For example, some of the meters tested had statistically detectable temperature and flow rate dependencies. These additional details are presented in the appendices of the original report.

* Meter failed during this test.

INSTRUMENTATION FOR LIQUID HYDROGEN DENSITY
MEASUREMENTS USING AN OPEN-ENDED MICRO-
WAVE CAVITY
Smetana, J., Wenger, N. C., NASA-LeRC
NASA TN D-6415, July 1971

OBJECTIVE. - Development of an instrumentation system, based on the resonant char-
acteristics of an open-ended microwave cavity, for measuring the density of liquid hy-
drogen and, in conjunction with a suitable volumetric flowmeter, for measuring total
mass flow rate or mass transfer.

PERTINENT WORK PERFORMED. - Design parameters for open-ended resonant cav-
ities have been established. Dielectric constants for liquid hydrogen as a function of
density are established and correlated with open-ended cavity resonant characteristics.
The effects of two-phase hydrogen (bubbles) on dielectric constant and density measure-
ments have been reviewed. A prototype model of a flow line section featuring a built-
in resonant cavity has been designed, fabricated and tested. Two resonant frequency
measurement electronic systems have been designed and fabricated, these are:
Resonant Frequency Tracking System (REFTS) and Cavity Tuned Oscillator (CTO).
Both systems have been performance evaluated and relative merits of each have been
determined. Limited systems testing has established system accuracies and
limitations.

MAJOR RESULTS. -

1. Steady state liquid hydrogen density measurements can be made to an accuracy of
   0.1% using the open-ended microwave cavity principle.

2. A practical flow line section with built-in resonant cavity has been fabricated and
   tested which demonstrates capability for making liquid density measurements to
   ±1.0% accuracy.

3. Two automatic resonant frequency measurement systems have been designed, both
   of which have demonstrated suitability for the application.

4. Acceptable two-phase density measurements can be made where the flow of liquid/
   gas is in a known configuration; however, problems associated with the measure-
   ment of random and slug flows have not been resolved in the investigation.

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PERFORMANCE CHARACTERISTICS OF LIQUID-VAPOR
SENSORS OPERATING IN A REDUCED GRAVITY ENVIRONMENT
Adams, R.G., et al., NASA-MSFC, TM 53840, May 1969.

OBJECTIVE. - To experimentally investigate the liquid retention and response charac-
teristics of certain liquid-vapor sensors when operating in low gravity environments.

PERTINENT WORK PERFORMED. - The complicated nature of fluid characteristics
in low-g environments prevented analytical predictions, hence all results were derived
from MSFC drop tower test data. This facility provided test durations of approximately
four seconds and gravity levels ranging from 5×10^{-4} to 0.03 of standard Earth gravity.
The experiments were executed by initially locating the sensor unit below the liquid
level in a transparent container of petroleum ether, then during the test, slowly
pulling the sensor above the liquid level. Sensor reaction to this procedure was
recorded by a motion picture camera and simultaneously electrical signals indicative
of sensor performance were obtained by telemetry.

MAJOR RESULTS. -

1. Seven types of liquid vapor sensors for use in low gravity environments have been
    experimentally investigated. Results of the tests definitely demonstrated that most
    of the sensors performed unreliably in low gravity environments. In general,
    during the low gravity test periods the probe sensing elements retained sufficient
    liquid to prevent sensor identification of the true (liquid or vapor) environment.
    The quantity of liquid trapped by each sensor was dependent on gravity level and
    probe geometry. Table I is a Summarization of Test Results, tabulating sensor
    types, acceleration levels, sensor orientation and sensor performance.

2. Test data revealed that, except for the optical and spiral types which performed
    successfully in the orientation tested, all other types were unsatisfactory for use
    in low gravity environments. Flight test data on the liquid-vapor capacitance
    type sensor manufactured by Transonics and a concentric ring type sensor manu-
    factured by Minneapolis Honeywell Corp, which were monitored by camera in
    flight,verified the unsatisfactory performances observed during this investigation.

COMMENTS. - This investigation demonstrates that zero-g performance of liquid-
vapor sensors, and possibly other sensors that may be required in low-g fluid transfer
systems,may present operational problems requiring careful investigation.

Table 1. Summarization of Test Results

Acceleration Level, a/g_e	Sensor Type	Sensor Orientation	Sensor Performance
0.01	Concentric Ring	Vertical	Unsuccessful
0.01	Concentric Ring	Vertical	Unsuccessful
0.01	Concentric Ring	Vertical	Unsuccessful
0.03	Concentric Ring	Vertical	Unsuccessful
0.01	Trans-Sonics	Vertical	Unsuccessful
0.01	Trans-Sonics	Vertical	Unsuccessful
0.01	Trans-Sonics	Horizontal	Successful
0.01	Trans-Sonics	Horizontal	Successful
0.001	Trans-Sonics	Horizontal	Successful
0.001	Trans-Sonics	Horizontal	Successful
0.001	Acoustic	Vertical	Unsuccessful
0.001	Acoustic	Vertical	Unsuccessful
0.001	Acoustic	Vertical	Unsuccessful
0.001	Bendix (Light Prism)	Horizontal	Unsuccessful
0.001	Bendix (Light Prism)	Horizontal	Unsuccessful
0.001	Bendix (Light Prism)	Horizontal	Unsuccessful
0.001	Bendix (Light Prism)	Horizontal	Successful
0.001	Bendix (Light Prism)	Horizontal	Successful
0.001	Flat Cable	Vertical	Unsuccessful
0.001	Flat Cable	Vertical	Unsuccessful
0.001	Flat Cable	Vertical	Unsuccessful
0.0005	Printed Circuit	Vertical	Unsuccessful
0.0005	Printed Circuit	Vertical	Unsuccessful
0.0005	Spiral Probe	Horizontal	Successful
0.0005	Spiral Probe	Horizontal	Successful

CRYOGENIC TEMPERATURE MEASUREMENT USING
PLATINUM RESISTANCE THERMOMETERS
Sinclair, D. H., et al, NASA-LeRC TN D-4499, April 1968.

OBJECTIVE. - Evaluation of commercial platinum resistance thermometers (PRT)
in order to satisfy need for accurate, reliable sensors to measure cryogenic
temperatures.

PERTINENT WORK PERFORMED. - The resistance-temperature function for pure
strain free platinum above 90°K is accurately expressed by the Callendar-Van Dusen
equation. Below 90°K, nonlinearity in the resistance-temperature (R-T) relations
is best expressed by Corruccini who used R-T relations in terms of resistance
differences (Z_T functions). These functions are best established by reference to NBS
calibration primary reference standard PRT. An evaluation of commercial PRT units
has been made based on Z_T functions derived from multipoint calibrations of statistical
samples compared with standard Z_T functions. Use of the Z_T function automatically
normalized the PRT calibrations in terms of nondimensional resistance ratios and at
the same time canceled out the effects of residual resistance. The average error
in the 20°K to 90°K range for primary reference NBS standards is taken to be less
than 0.005°K. Based on and utilizing the foregoing concepts a comprehensive survey
was made of the performance characteristics of commercially available platinum
resistance thermometers. Other features tested were; reliability, residual ratios,
repeatability and self heating. Tested units included twelve basic commercial types,
three Lewis Research specified improved types and a unit of poor quality. Instrumen-
tation and procedures for improved calibrations in the cryogenic ranges were detailed.

MAJOR RESULTS.

Evaluation of three types of commercial PRT transducers demonstrated that
resistance difference ratio "Z" functions based at 20.20°K and at 77.4°K conform
to the primary reference PRT to within ±0.04°K. Accuracy in the range of
77.4°K to 273.15°K was found to be the same. Table I presents a detailed
tabulation of data along with the corresponding data of a Primary Standard NBS
thermometer.

TABLE I. – COMPARISON OF PLATINUM RESISTANCE THERMOMETERS[a]

Manufac- turer	Type	Reliability		Temperature, T, °K						Residual ratio, R_{20}/R_{77}, percent	Repeatability at 20° K, ±°K	Self-heating in liquid nitrogen, °K/mW	Cost, dollars
		Tested	Failed	273	77.4	20.2	77	20	20				
				Resistance, R, ohm			Sensitivity						
							$\partial R/\partial T$, ohm/°K		$\partial R/(R\,\partial T)$, %/°K				
A	1	3	0	5000	945	25.5	21.6	3.8	14.8	2.7	0.01	0.02	190
A	2	3	2	200	38.2	.96	.87	.15	15.6	2.5		.04	100
A	3	3	2	500	95	2.97	2.1	.38	12.8	3.1		.07	80
B	4	3	0	1340	260	18	5.8	1.0	5.6	6.9		.02	280
B	5	3	0	500	94.5	2.55	2.1	.38	14.8	2.7		.02	140
B	6	5	1	435	83	2.5	1.9	.33	13.2	3.0		.01	40
C	7	3	2	4770	925	51.5	20.5	3.7	7.2	5.6		.01	350
C	8	3	1	500	96	4.17	2.1	.38	9.1	4.3		.02	190
C	9	3	1	455	90	7.28	2.0	.35	4.8	8.1		.11	120
D	10	3	0	100	19.8	1.5	.43	.077	5.1	7.6		.01	20
E	11	3	1	335	63.3	1.66	1.45	.26	15.7	2.6		.07	330
E	12	3	2	183	35	.85	.79	.14	16.5	2.4	.03	.04	180
A	13	51	0	5000	945	25.5	21.6	3.8	14.8	2.7	.01	.02	190
A	14	51	0	1380	261	6.6	5.9	1.04	15.7	2.5	.01	.02	170
A	15	202	1	1000	189	4.86	4.3	.74	15.2	2.6	.01	.03	140
F	16	19	8	335	64	5.0	1.4	.26	5.2	7.8	.10	.05	50
P	S	7	3	25.5	4.81	.11	.11	.019	17.3	2.29	.005	.02	450

Basic Types (A 1–E 12); Improved (A 13–A 15); Poor Quality (F 16); NBS (P S)

[a]Nominal values.

NUCLEONIC MEASUREMENTS OF CRYOGENIC

DENSITIES AND QUALITIES, Scheiwe, J. P., Cho, B. Y.,

Industrial Nucleonics Corp., Nucleonics in Aerospace,

Proceedings of the Second International Symposium,

Columbus, Ohio, July 12-14, 1967, Plenum Press, 1968

OBJECTIVE. - This paper presents the design and operational principles used in nucleonic gauges built by Industrial Nucleonics Corporation for the measurement of density and quality of low temperature hydrogen. Performance data for both types of gauges are presented and evaluated.

PERTINENT WORK PERFORMED. - The fast response cryogenic (LH_2) densitometer built for NASA was a modified commercial quality meter built for Douglas Aircraft Corp. The cryogenic quality meter was built to NASA Saturn specifications, to measure the quality of two-phase saturated hydrogen vented from the S-IVB stage of the Saturn vehicle. The densitometer gamma radiation source was Cesium 137 with a multiplate ionization chamber detector. The quality meter radiation source was Am-241 with a Sodium Iodide crystal detector coupled to an EMI photomultiplier tube. The densitometer was tested at the Instrument Development Branch Test Laboratory of Geo. C. Marshall Space Flight Center. In testing for LH_2 density, measurements were made of density, vapor pressure and temperature. Liquid hydrogen density was calculated by means of the following equation:

$$\rho(T) = 8.440 \times 10^{-2} - 2.230 \times 10^{-4} \, T - 2.183 \times 10^{-5} \, T^2$$

The quality meter was performance evaluated in connection with the flight of the S-IVB stage of the saturn flight of June 1966. The equation defining quality was as follows:

$$Q = \frac{\text{Vapor (Mass)}}{\text{Liquid (Mass)} + \text{Vapor (Mass)}}.$$

MAJOR RESULTS. -

1. Performance of the densitometer was checked through LH_2 changes associated with the following: Temperature changes, venting, supercooling, and restabilization. Figure 1 shows a plot of these results against calculated values. Static accuracies of ±0.3% and dynamic accuracies of ±3.0% were demonstrated under laboratory conditions.

2. Performance of the densitometer in LH_2 slush demonstrated accuracies of 0.5%.

3. Performance of the quality meter during the S-IVB flight demonstrated encouraging results during high level mass-flow (80%) liquid conditions and showed good correlation with TV data taken during venting periods.

4. The suitability of nucleonic methods of instrumentation for density and quality measurements has been demonstrated for space operations. It has been proposed to modularize these systems and to extend their application to include flow rate measurement of two-phase flow.
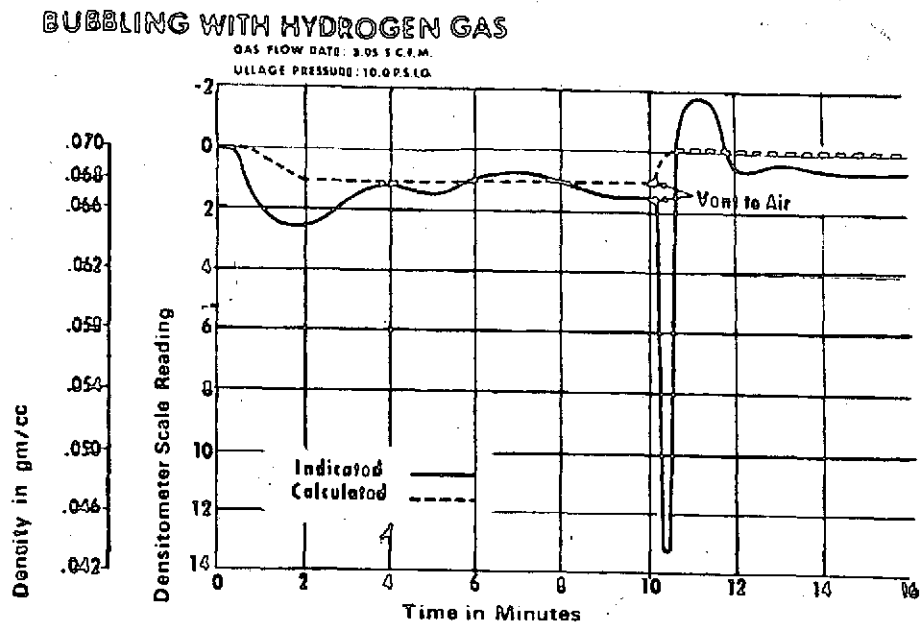
Figure 1. Time Varying Liquid Hydrogen Density
Data

AN EXPERIMENT TO TEST LOW LEVEL ACCELEROMETERS
Vandervelde, W. E., MIT, Air, Space and Instruments, Draper Anniversary
Volume, New York, McGraw-Hill Book Co., Inc. 1963

OBJECTIVE. - To devise and define a technique for testing/calibrating micro-g
accelerometers.

PERTINENT WORK PERFORMED. - A method has been proposed and analyzed which
provides a practical means of testing accelerometers under otherwise weightless con-
ditions with inputs from 10^{-5} g to 1g. Basic to this proposal is that the testing is to
be performed in an aircraft flying a parabolic arc so as to produce a zero-g condition
for discrete periods. A free floating centrifuge is proposed along with a gyro con-
trolled gimbal on which a speed clocked camera is mounted for determining angular
velocity. The test accelerometer, power supplies and accelerometer output recording
means are mounted in a counter-balanced configuration as an integral part of the cen-
trifuge. An error analysis has been conducted to determine the effect of angular vel-
ocity uncertainty, effective radius length uncertainties, and aerodynamic effects.

MAJOR RESULTS. -

1. A free floating zero-g centrifuge has been proposed for testing/calibrating micro-g
   accelerometers under essentially weightless conditions in the range of 10^{-5}g to 1g
   levels.

2. Means for manipulating and monitoring a micro-g centrifuge and for acquisition of
   accelerometer data has been outlined.

3. The accuracy of calibration levels is 0.1% of the input acceleration in the range of
   0.1 to 0.0002 g's increasing up to 0.7% at 10^{-5}g's.

4. The programmed system is amenable to design refinements which can extend the
   lower limits of the experiment to meet the requirements of tomorrow's low-level
   accelerometers.

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6.0 STRATIFICATION/PRESSURIZATION

Covering fluid temperature stratification and tank pressurization
with and without liquid outflow, with and without external press-
urization with condensible and/or non-condensible gases, and
with and without venting.

GASEOUS-HELIUM REQUIREMENTS FOR THE DISCHARGE
OF LIQUID HYDROGEN FROM A 3.96-METER (13-FT.)
DIAMETER SPHERICAL TANK
Stochl, R. J., NASA-LeRC, TN D-7019, December 1970

OBJECTIVE. - Determine the effects of various physical parameters on helium pres-
surant gas requirements during initial pressurization and during expulsion of LH_2 and
compare test results with an analytical model.

PERTINENT WORK PERFORMED. - Testing was accomplished in a 3.96-m (13-ft.)
diameter 2219-T87 aluminum alloy spherical tank located in a vacuum chamber. Tests
were conducted for a range of liquid outflow rates (1.73 to 4.32 Kg/sec) at a constant
pressure of $34.47 \times 10^4 N/m^2$ (50 psia) using a hemisphere type injector. Data were
also obtained for pressurization of the tank from 1 atm. to 50 psia with no outflow at
various pressurant inflow rates (2.48×10^3 to 8.96×10^3 N/m^2-sec) for initial tank
ullages of 5, 28, 55, and 75% of total tank volume. In addition to pressure data, tem-
peratures were recorded throughout the tank. An unsuccessful attempt was made to
measure the concentration of helium and hydrogen gas at five positions in the tank.

The basic analytical program developed by Roudebush, 1965 (TN D-2585), and illus-
trated in Figure 1, was used for comparison with the test data. Modifications made
to the basic program were accomplished to allow application to arbitrary symmetric
tank shapes, and an attempt was made to incorporate heat transfer from the gas to
the liquid. The treatment of internal hardware (e.g., tank baffles and instrumentation)
was also modified to correspond to the treatment of heat transfer to the tank wall.

MAJOR RESULTS. -

1. Increasing the inlet gas temperature and/or the pressurization rate with no outflow
   reduced pressurant requirements.

2. The trends for various inlet gas temperatures and liquid outflow rates were consis-
   tent with results using hydrogen as the pressurant (Stochl, et al, 1969). The ratio
   of ideal to actual pressurant for similar test conditions was 8.3% lower for helium
   than for hydrogen. The trends were also consistent with those from smaller tank
   (1.52-m-dia.) tests indicating that scale effects are predictable.

3. For the range of test conditions used, the analytical program and assumptions ade-
   quately predicted pressurant gas requirements during the initial pressurization as
   well as during the expulsion period; within 2.1% for the 300K inlet temperature
   and within 7.0% for the 168K case. Tank wall heating predictions were within 19.3%,
   however, the prediction of liquid heating was not good (average deviation of 41.9%).

Figure 1. Pertinent Computer Program Characteristics (Roudebush, 1965)
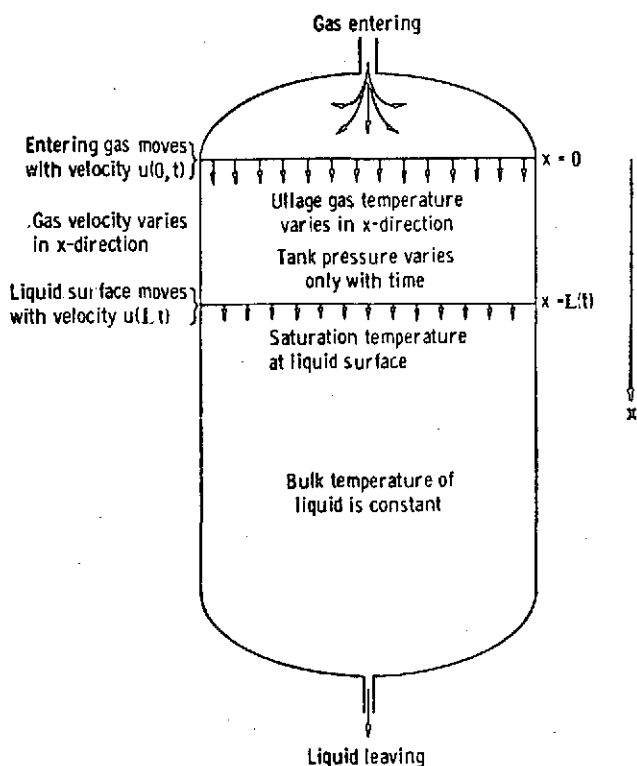
(1) The ullage gas is nonviscous.

(2) The ullage gas velocity is everywhere parallel to the tank axis and does not vary radially or circumferentially.

(3) The tank pressure does not vary spatially.

(4) The ullage gas temperature does not vary radially or circumferentially.

(5) The tank wall temperature does not vary radially or circumferentially.

(6) No heat is transferred axially in either the gas or the wall.

(7) No condensation or evaporation occurs.

(8) No heat is transferred from the gas to the liquid.

TRANSIENT PRESSURE RISE OF A LIQUID-VAPOR SYSTEM
IN A CLOSED CONTAINER UNDER VARIABLE GRAVITY
Merte, H., et al, Univ. of Mich., 4th Int. Heat Transf. Conf.,
Paris, France, September 1970

OBJECTIVE. - Develop an analytical model and correlate with actual flight data for
prediction of pressure rise in a closed cryogenic container at low-g.

PERTINENT WORK PERFORMED. - The analytic problem was formulated in terms of
the transport equations for a cylindrical tank with an axial body force and a symmetri-
cally imposed external heat flux (Figure 1). The tank ends are assumed adiabatic.
The temperature and velocity distributions are determined using a finite-difference
method, which is coupled with an integral form of the energy equation to determine
pressure rise. The procedure takes into account the possibility of incipient and
nucleate boiling. For convection heat transfer it is assumed that laminar conditions
prevail. When the temperature of the wall in contact with the liquid exceeds the
saturation temperature by a specified amount, nucleate boiling is initiated. The boiling
model considers that all vapor formed proceeds directly to the ullage space without
interaction with the liquid. All properties are assumed constant except the density
in the body force term, and viscous dissipation is neglected. In the vapor region an
ideal gas is assumed. The processes in the liquid and vapor regions are coupled
at the interface by evaporation or condensation depending on the relative rates of
diffusion heat transfer. The governing equations are made non-dimensional and
placed in finite difference forms, along with boundary conditions for solution.

Calculations were made for the Saturn AS-203 hydrogen tank as approximated by a
cylinder 6.7-m-dia. by 8.9-m-high, 1/3 filled with liquid. The total energy input was
approximately 9 Kcal/sec., however, since some uncertainty existed as to heat flux
distribution this was varied in the computer model. Also, different wall materials
were used to assess their influence (Table 1). The effective acceleration was a/g =
1.7×10^{-4} and the superheat for nucleate boiling to take place was 0.55°C. Comparisons
between computer and flight data are presented in Figure 2.

MAJOR RESULTS. - Comparison of the computer model with the flight data was not
good. This was thought to be due primarily to three factors; (1) having flat ends,
the distribution of heating in relation to the liquid and vapor volumes was not satis-
factorily simulated, (2) interaction of vapor bubbles with the liquid, neglected here,
would tend to increase the pressure-rise rate and (3) neglecting $\partial p / \partial$ time
in the vapor space would produce lower densities and hence lower pressure.
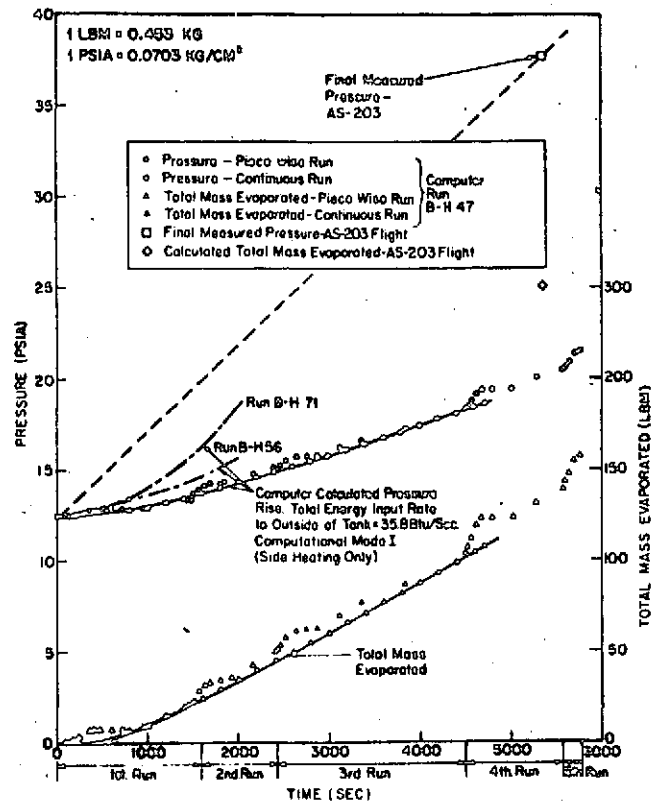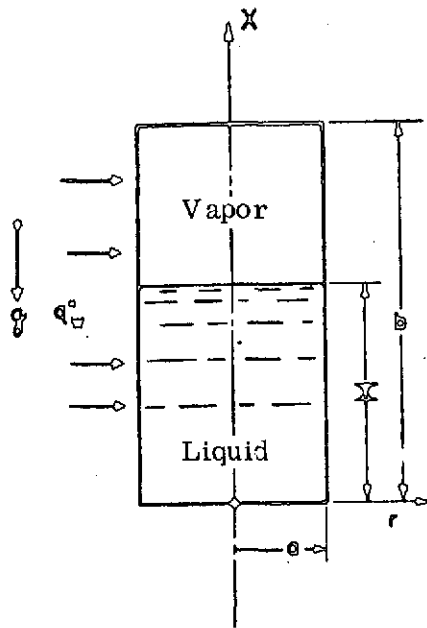
Figure 1. Container Coordinate System

Figure 2. Computed Pressure Rise

Run No.	Nucleate Boiling Permitted	Wall Material	qw – watts/cm^2	
			Liquid	Vapor
B-H 47	Yes	Polyurethane	.0521	.0049
B-H 56	Yes	Aluminum	.0202	.0202
B-H 71	No	Aluminum	.0202	.0202

Table 1. Parameters for Computer Runs

EVALUATION AND APPLICATION OF DATA FROM LOW-
GRAVITY ORBITAL EXPERIMENT, Bradshaw, R. D., et al, GD/C
GDC-DDB70-003, NAS8-21291, April 1970

OBJECTIVE. - To analyze the S-IVB-AS-203 flight data and other available data to
determine the applicability and adequacy of analytical models in several areas of
thermodynamics and fluid mechanics.

PERTINENT WORK PERFORMED. - Work was accomplished in the areas of repres-
surization, closed tank pressure rise, liquid level phenomena during venting (venting
effects) and propellant sloshing. Only the closed tank pressure rise work will be
discussed here. Pressure rise correlations were performed for the hydrogen tank for the
4th orbit of the AS-203 flight. Two different analytical models were used to predict
the flight data. The first model is basically the Saturn II pressurization program
described in the summarized report by Nein and Thompson, 1966 (TND-3177). For
discussions here, this model is referred to as the P3542 program.

The second model is the REPORTER program developed under Contract NAS8-20165 by
Walburn, et al, 1967. This program represents a First Law thermodynamics analysis
with capacity for a 10 node problem, permitting temperature stratification in the
ullage; however, for the current application only a single ullage and a single liquid
node were used. Prior to the actual pressure rise analysis, considerable effort was
expended in obtaining and verifying the external heating for input to the thermodynamic
models. The heat transfer analysis within the forward skirt area proved difficult
because of an undefined absorptivity α for the Mylar insulation on the forward dome.
This absorptivity was estimated to be anywhere from 0.05 to 0.55 with a nominal value
chosen as 0.20.

MAJOR RESULTS. -

1. Comparisons of analytical predictions with test data are presented in Figure 1,
    showing fairly good agreement, depending on the value of absorptivity used for
    the H_2 tank dome. Case 1 for the P3542 program corresponds to a total ullage
    heating, as calculated by the program, of 50,160 Btu while for Case 2 this is
    55,800 Btu. The actual estimated heat input from a detailed analysis using a
    heat conduction program was 53,700 Btu. Matching of the heat flux calculated
    in P3542 with that predicted is a cut-and-try process.

2. Both programs are dependent on good data for ullage heating and both are
    inadequate relating to liquid stratification and propellant boiloff contributions.
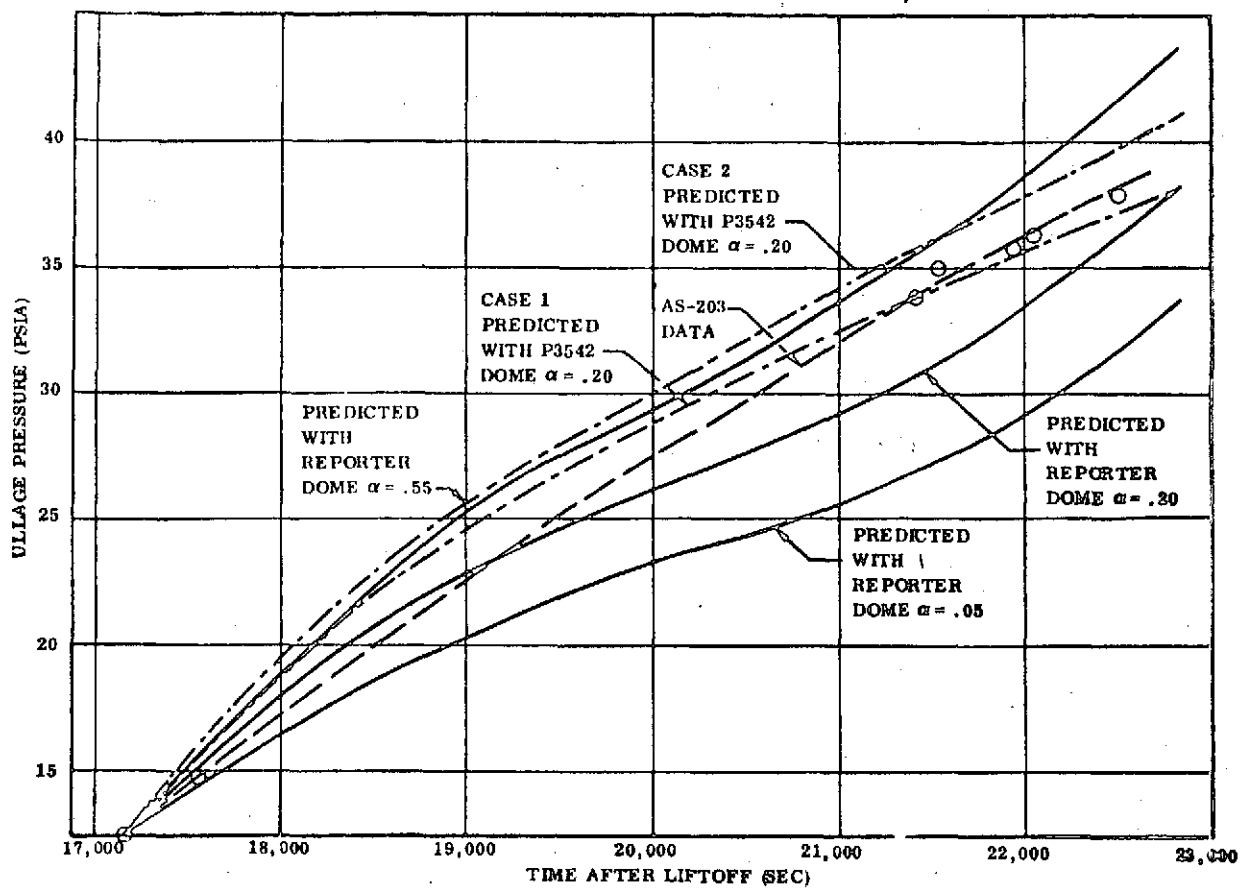
Figure 1. Comparison of Predicted Pressures With AS-203 Pressure History During Long Term Coast

PRESSURANT GAS REQUIREMENTS FOR THE PRESSURIZED
DISCHARGE OF LIQUID HYDROGEN FROM PROPELLANT TANKS
Stochl, R. J. and DeWitt, R. L., NASA-LeRC, TMX-52573,
June 1969

OBJECTIVE. - Experimentally determine the effect of various physical parameters
on pressurant gas requirements and demonstrate the capability of analysis to predict
these requirements during expulsion of LH_2.

PERTINENT WORK PERFORMED. - Testing was accomplished for: (1) two 5-ft (0.3-
in. and 0.161-in. 6061 Al Aly wall) and one 13-ft (0.50-in. 2219 Al Aly wall) diameter
spherical tanks, (2) three different injector geometries (hemispherical and radial dif-
fusers and a straight pipe), (3) inlet gas temperatures of 300°, 500°, and 640° R, (4)
tank pressures of 35, 50, and 75 psia, (5) liquid outflow rates of 0.5 to 12 lb/sec,
and (6) expulsions with and without slosh. In all cases, expulsion was at constant
pressure using GH_2. Initial ullage was 5% and expulsion was stopped at 95% liquid
expulsion. The criteria for comparison was the ratio of ideal pressurant mass (no
energy loss to walls or liquid) to the actual pressurant mass used. Testing was done
in a vacuum chamber and fluid temperatures, tank pressure and liquid outflow and
pressurant inflow rates were measured. Individual energy losses to the tank wall, in-
ternal hardware and liquid were determined.

MAJOR RESULTS. -

1. Of all test variables, the inlet gas temperature had the strongest effect (Figure 1).
   Also, in all cases the amount of pressurant required increased for increasing ex-
   pulsion time (Figure 2). Changing tank pressure level does not alter the ratio of
   ideal to actual pressurant.

2. The use of a straight pipe injector decreases pressurant requirements over that of
   the diffuser types (Figure 3). This decreased pressurant requirement is due to
   reduced tank wall heating and greater amounts of liquid evaporation.

3. The major heat sink is the tank wall, where 40 to 50% of the total energy is ab-
   sorbed; 15 to 20% is absorbed by the liquid.

4. Sloshing of the liquid at its natural frequency causes a significant increase in pres-
   surant requirement (Figure 4). Although the use of antislosh baffles decreases the
   wave height, it also causes more liquid splashing which cools the ullage gas.

5. In general, the analytical program of Roudebush, 1965, was able to predict
   pressurant requirements within ±10% for all no slosh tests except for the straight
   pipe injector data which was within ±30%.

Figure 1. Pressurant Mass Ratio as a f (Inlet Temperature) for Two Tank Sizes

P_T = Tank Pressure
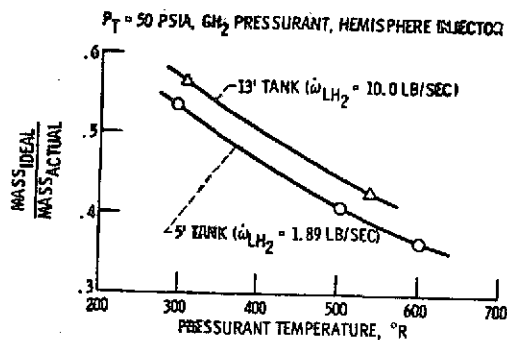$\overset{\circ}{\omega} = \overset{\circ}{W}$ = Outflow Rate (lbs/sec)
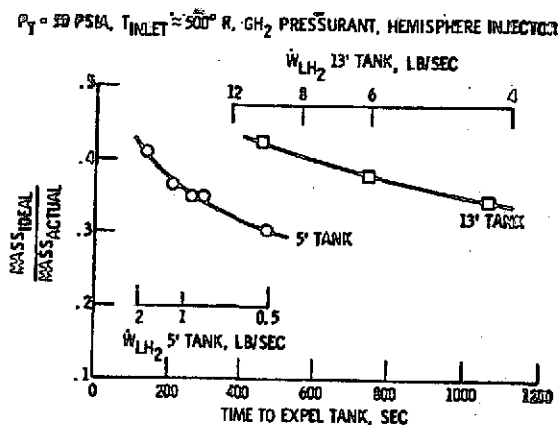
Figure 2. Pressurant Mass Ratio as a f (Expulsion Time) for Two Tank Sizes
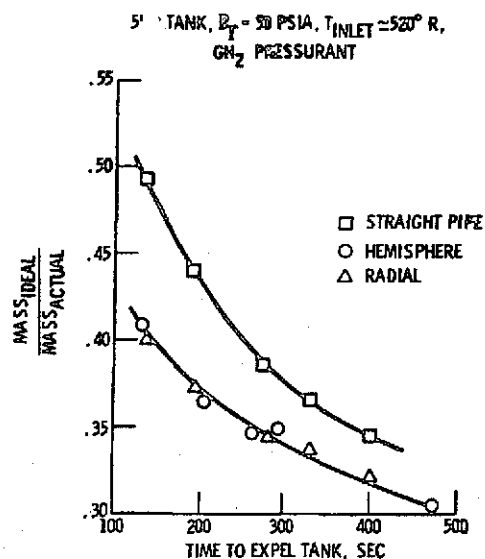

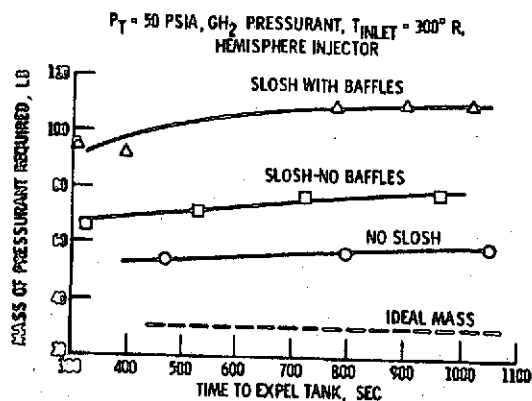Figure 3. Pressurant Mass Ratio as a f (Expulsion Time) for Three Injector Geometries

Figure 4. 13' Tank Pressurant Gas Requirements Under Slosh Conditions

MODULAR NUCLEAR VEHICLE DESIGN, VOL. IV -
ASYMMETRIC PROPELLANT HEATING COMPUTER
PROGRAM, LMSC, A794909-A, NAS8-20007,
September 1968

OBJECTIVE. - To develop a stratification and pressurization model and computer code.

PERTINENT WORK/MAJOR RESULTS. - The computer code developed results from
work at LMSC under various company and contracted programs, including NAS8-11525
(Hurd, 1966 and Chin, 1965 and 1964). The model treats a draining axisymmetric
(single-valued radius) vessel which can have variable acceleration and asymmetric
heating. The liquid is treated stepwise-in-time and is broken into stratified layers
with quasi-steady turbulent (1/7 power profile) boundary layer flow (Figure 1). Earlier
versions included laminar boundary layers, however, computations were unstable.
Asymmetric heating is treated by breaking the vessel into wedges about the center-line.
Direct bulk (nuclear) heating can be included. Pressurization or venting is treated
continuously with time and the ullage is coupled with the liquid and wall through mass
and/or energy transfer. The ullage is a single vapor node (no non-condensibles) as is
the wall. The liquid surface is flat and the isotherms are horizontal, except in the
boundary layer (assumed thin compared to vessel radius). Each of the azimuthal wedges
has its own boundary layer and, based on experimental data from NAS8-11525, is
assumed to have no edge effects. The boundary layer on each wedge initiates from its
inversion point (arbitrarily chosen or determined from a balance between buoyant and
pressure forces). Below the inversion point, simple mixing with the adjacent bulk
fluid is assumed. The surface liquid layer is limited to a specified minimum mass by
combining layers as needed.

After each step of liquid stratification, pressurization is considered. Pertinent aspects
are illustrated in Figure 2. Compression heating of the liquid, determined to be
important during LH_2 testing in a 40-in dia tank at LMSC, is included. Previous test
work (references not given) indicate that flows at the L/V interface are complex and
therefore heat transfer coefficients at the interface are input to the program and must
be estimated or determined from empirical data. The energy balance at the interface is:
$*h_{fg} \dot{m}_s = \dot{Q}_{us} - \dot{Q}_{Ls} = [h_{us} (T_u - T_s) - h_{Ls} (T_s - T_L)] A_s$. If $\dot{Q}_{us} > \dot{Q}_{Ls}$ evaporation will
occur and if $\dot{Q}_{us} < \dot{Q}_{Ls}$ condensation will occur. It is assumed that subcooled ullage or
superheated liquid cannot occur and is prevented by appropriate liquid evaporation.

At the end of each time step the following are output: temperature, mass thickness and
position of each layer remaining; temperature and mass of each layer drained; ullage
pressure, temperature and mass; wall temperature; mass transfer at L/V interface;
mass of pressurant added or mass of vapor vented.

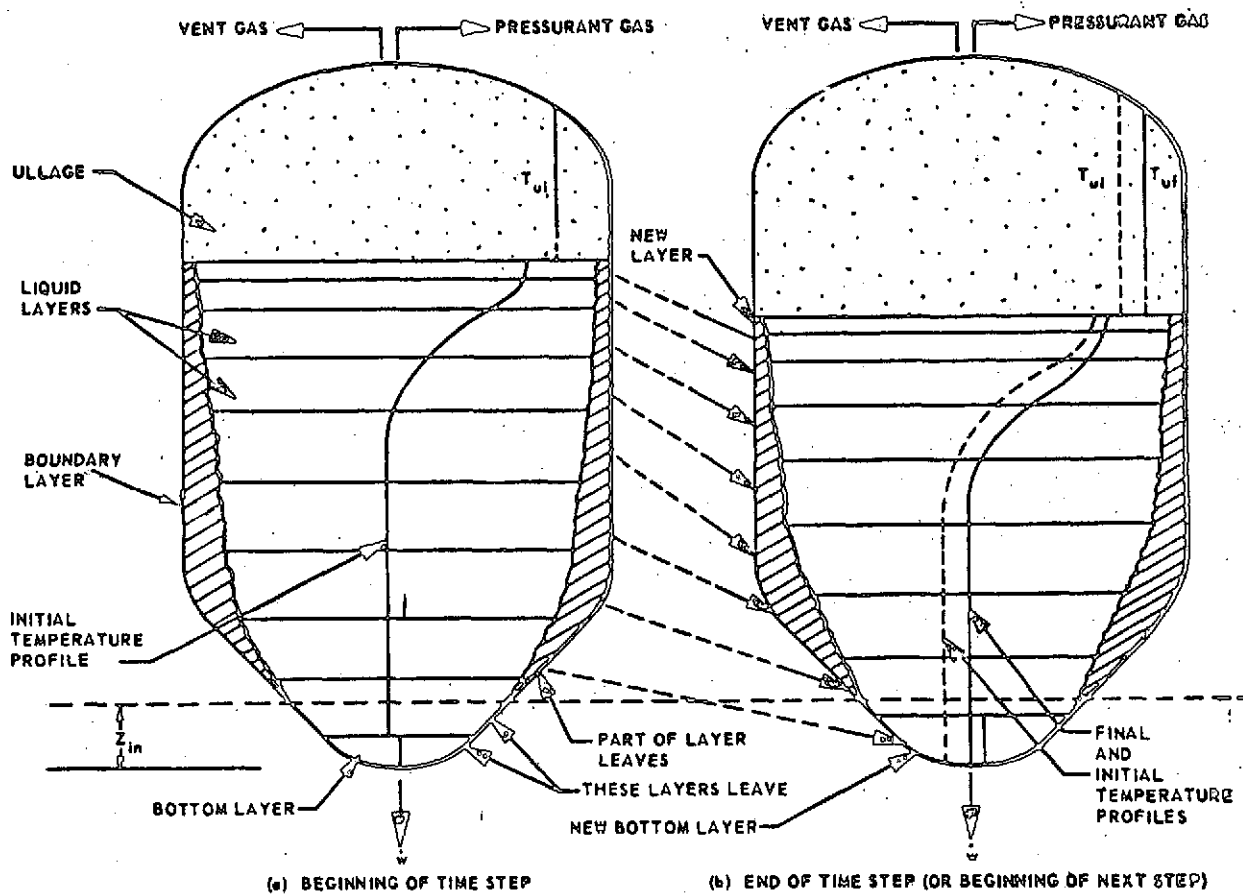* Subscripts u, s and L refer to the ullage, liquid surface and liquid bulk, respectively.
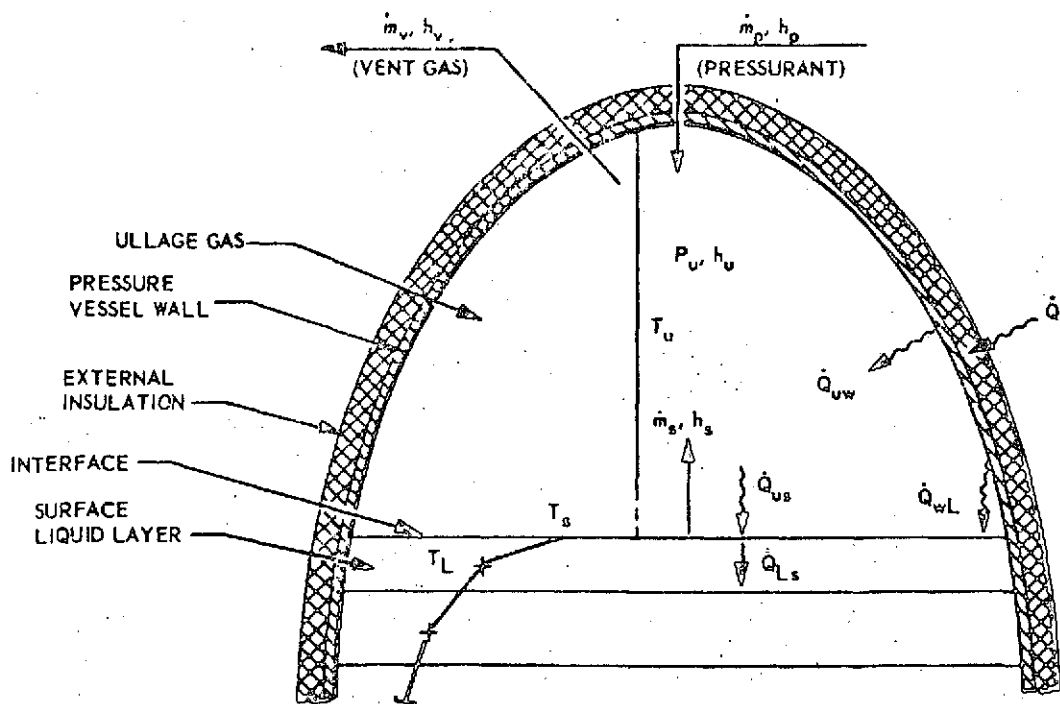
Fig. 1. Configuration at Beginning of Time Steps

Fig. 2. Configuration for Liquid-Ullage Wall Coupling

6-11

EMPIRICAL CORRELATIONS FOR PRESSURE RISE IN
CLOSED CRYOGENIC CONTAINERS, Blatt, M. H., GD/C

OBJECTIVE. - To define a simple method of predicting pressure rise in a closed
cryogenic tank subjected to external heating under both 1-g and "zero-g" conditions.

PERTINENT WORK PERFORMED. - A logical relationship between pressure rise and
tank conditions for a stratified fluid was postulated to be $\Delta P/\Delta t = C_1 (\dot{Q}/MS)^{C_2}$, where
M is total fluid mass and S is percent ullage. A least squares fit was then made of
available data for which the above parameters were known. In the case of LH_2 at
"zero-g", a total of 10 data points were available from SIVB-203 and Aerobee flights.
For LH_2 at 1-g, NASA/LeRC, Los Alamos, Aerobee and AC-9 (Atlas-Centaur) data
provided 5 points. For LO_2 at 1-g, insufficient data was found to attempt a correlation.
At 0-g, Atlas-Centaur provided 3 data points. The maximum percent deviation was
+89/-35% for zero-g H_2, +42/-15% for 1-g H_2 and +6/-1% for zero-g O_2.

MAJOR RESULTS. - The following equations were developed from the least square
fit:

LH_2 - "zero-g" $\quad \Delta P/\Delta t = 86 (\dot{Q}/MS)^{0.975} \quad\quad$ Eqn. 1

LH_2 - 1-g $\quad\quad \Delta P/\Delta t = 98 (\dot{Q}/MS)^{1.02} \quad\quad$ Eqn. 2

LO_2 - "zero-g" $\quad \Delta P/\Delta t = 1450 (\dot{Q}/MS)^{1.14} \quad\quad$ Equ. 3

In the above equations, $\Delta P/\Delta t$ is in psi/hr, $\dot{Q}$ = total heat input in Btu/hr, M in LB
and S in percent. These equations are shown plotted in Figure 1, along with data for
homogeneous pressure rise for comparison. The homogeneous pressure rise equations
are:

LH_2 $\quad\quad \Delta P/\Delta t = 1.13 (\dot{Q}/M)^{1.01} \quad\quad$ Equ. 4

LO_2 $\quad\quad \Delta P/\Delta t = 3.58 (\dot{Q}/M) \quad\quad$ Equ. 5

These homogeneous equations are approximations and are only accurate at ullage vol-
umes where the energy and mass contributions of the ullage are negligible.

COMMENTS. - The equations developed are based on a fairly small amount of data
and should, therefore, only be used where it is required to determine an approximate
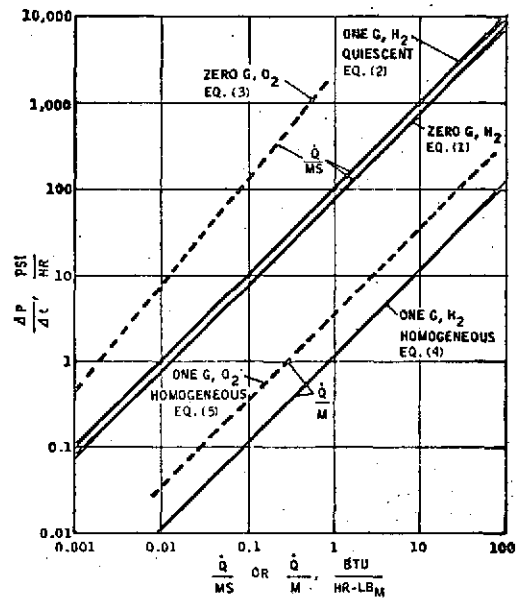pressure rise with a minimum of calculation.

Figure 1. Comparison of Tank Pressure
Rise Rate Correlations

EFFECT OF GRAVITY ON SELF-PRESSURIZATION
OF SPHERICAL LIQUID-HYDROGEN TANKAGE
Aydelott, J. C., NASA-LeRC,TND-4286, Dec. 1967

OBJECTIVE. - To examine information from several experimental programs in order
to understand the thermodynamic history of liquid-hydrogen tankage at both normal and
reduced gravity.

PERTINENT WORK PERFORMED. - Heat transfer test data, primarily in the form of
non-vented pressure rise rates, are reviewed from a series of Aerobee flights, an Atlas
passenger pod flight and 1-g tests with variations in heat distribution (Aydelott, 1967).
In all cases the test tank was basically the same configuration (Fig. 1); consisting of a
9-in (23-cm) dia CRES inner sphere containing the LH_2, an intermediate sphere with
electric heating coils and an outer vacuum jacket. Two simple pressure rise models
are presented for comparison with the test data; (1) homogeneous and (2) surface
evaporation which assumes all the energy absorbed goes to evaporating liquid and
maintaining the vapor at a temperature corresponding to saturation at the total pressure
while the liquid temperature remains constant.

MAJOR RESULTS. -

1. Overall, the location of heat input relative to the liquid and vapor was the most
   important factor in determining pressure rise rates. This is illustrated for the
   1-g case in Figure 2.

2. Under reduced-gravity the pressure rise was greatly affected by the liquid
   configuration, with totally wetted walls producing the lowest rise rate. The liquid
   configuration was in turn dependent on the heat transfer rate and distribution, on
   the percent liquid fill and possibly on the existence of internal instrumentation.
   High heat-transfer rates and low liquid filling decreased the wetted area and in-
   creased pressure rise rates (Figure 3). Also, a small unidirectional acceleration
   decreased the wetted area and increased the rise rate. Oscillatory or random
   disturbances decreased the rise rate.

3. In general, pressure rise rates at 1-g quiescent were greater than at low-g (Fig. 4)
   since (a) the wetted wall area increased with decreasing g-level and (b) as g-level
   is reduced, convective heat transfer is diminished and boiling enhanced, with an
   increasing bubble population acting to cause more complete liquid mixing.

COMMENTS. - Statement 3b above appears to be mostly speculation with no real
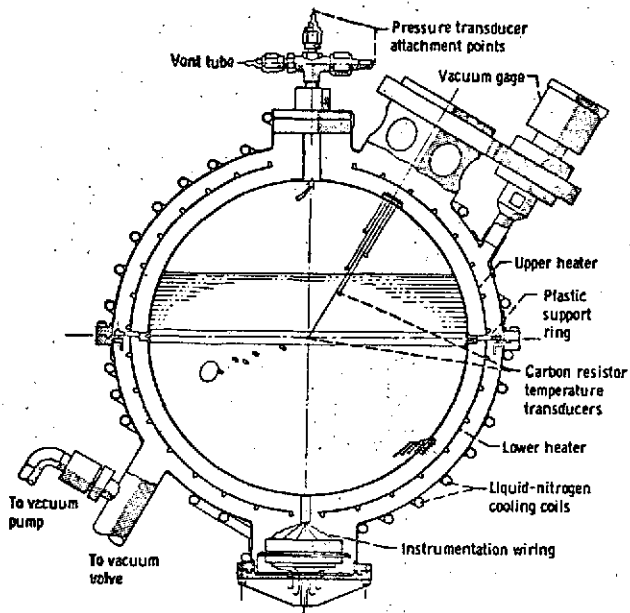quantitative verification within this report.

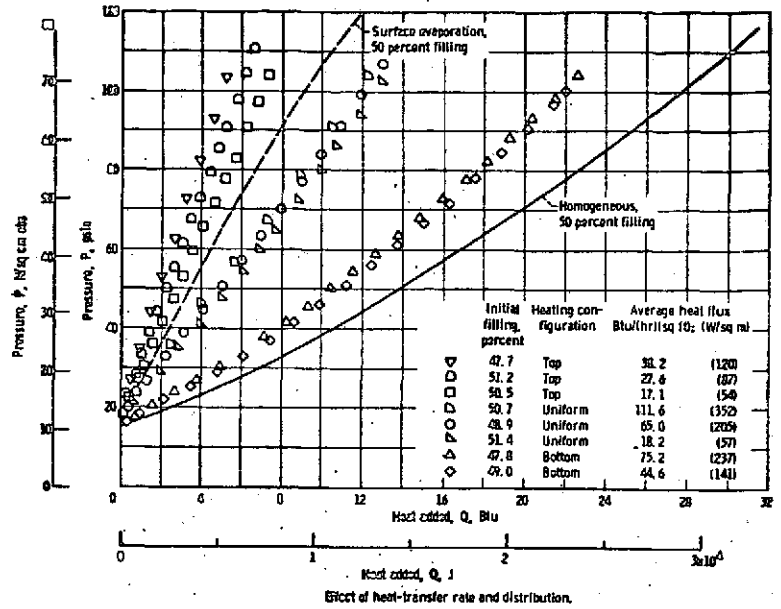Figure 1. Apparatus for Typical Aerobee Experiment

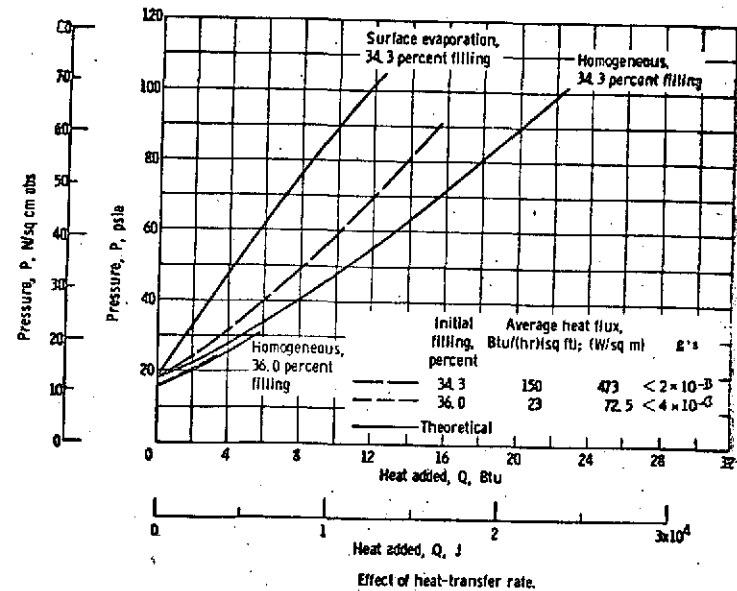Figure 2. Effect of Heat–Transfer Rate and Distribution

Figure 3. Pressure as Function of Heat Added; Comparison of Normal-Gravity and Reduced-Gravity Tests. Uniform Heating Configuration
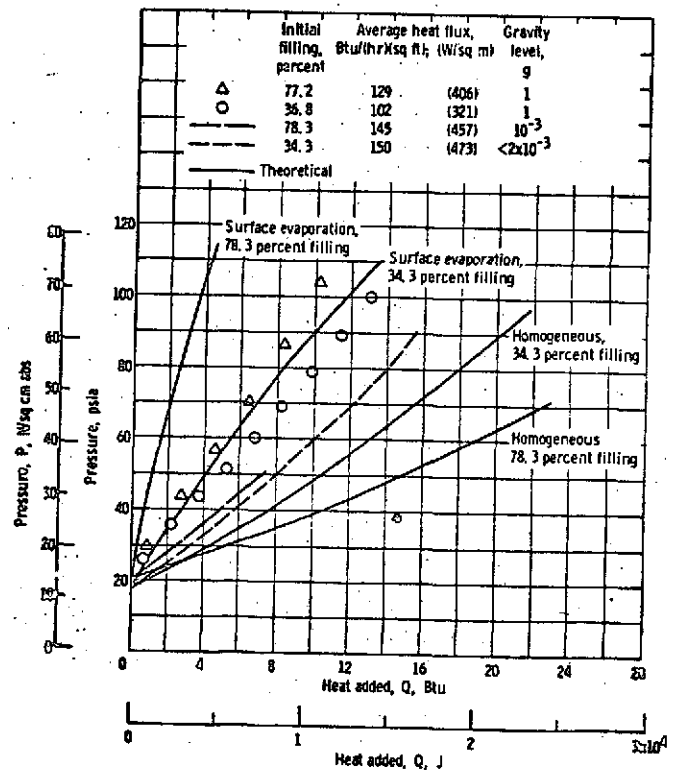

Figure 4. Pressure as Function of Total Heat Added for Reduced-Gravity Tests. Uniform Heating

AN EQUATION FOR THE PREDICTION OF CRYOGENIC PRESSURANT REQUIREMENTS FOR AXISYMMETRIC PROPELLANT TANKS

Epstein, M., Anderson, R. E., NAR, Advances in
Cryo. Engr., Vol. 13, August 1967

OBJECTIVE. - Develop a simple equation for prediction of pressurant requirements
to maintain essentially constant pressure outflow of settled cryogenic fluids.

PERTINENT WORK PERFORMED. - The form of the equation and the dimensionless
groups employed were obtained from the theories of Gluck and Kline, 1962, and
Arpaci, et al, 1961. The coefficients were derived by fitting more than 125 theoretical
points obtained by the generalized pressurization computer program described by Ep-
stein, et al, 1965, and Nein and Thompson, 1966, over the range of variables pre-
sented in Table 1. The deviations of the pressurant requirements predicted by the
program from those obtained from the equation were less than 7%. The equation was
also compared with a considerable amount of test data. The final equation is pre-
sented below.

$$\frac{w_p}{w_p{}^0} = \left\{ \left(\frac{T_0}{T_s} - 1\right)[1 - \exp(-p_1 C^{p_2})][1 - \exp(-p_3 S^{p_4})] + 1 \right\}$$

$$\times \exp\left[-p_5 \left(\frac{1}{1+C}\right)^{p_6} \left(\frac{S}{1+S}\right)^{p_7} Q^{p_8} \right] \qquad (1)$$

where

$$w_p{}^0 = \rho_G{}^0 \Delta V \qquad C = \frac{(\rho c_p{}^0 t)_W}{(\rho c_p)_G^0 D}\left(\frac{T_s}{T_0}\right) \qquad S = \frac{h_c \theta_T}{(\rho c_p)_G^0 D}\left(\frac{T_s}{T_0}\right) \qquad Q = \frac{\dot{q}\theta_T}{(\rho c_p)_G^0 D T_0}$$

D = equivalent tank diameter. (Diameter of a cylindrical tank having same total volume
and wall surface area as tank under investigation)
h_c = gas-to-tank-wall-free-convection heat transfer coefficient. (Calculated at film
temperature equal to $(T_0 + T_s)/2$ and temperature difference equal to $T_0 - T_s$)
p = tank pressure during liquid expulsion
$p_1...p_8$ = fitted constants (Table 2).
$\dot{q}$ = heat flux from ambient to tank wall, per surface area of wall
t_W = wall thickness
T_0 = pressurant inlet temperature
T_s = saturation temperature of propellant at initial tank pressure. (Equivalent to the
initial wall temperature)
w_p = total pressurant mass
$w_p{}^0$ = total pressurant mass under conditions of zero heat and mass transfer
$w_p/w_p{}^0$ = collapse factor
ΔV = expelled liquid volume
θ_T = total liquid outflow time
ρ = density
Subscripts
G refers to gas
W refers to wall
Superscript
O refers to variables at a temperature equal to inlet pressurant temperature and a
pressure equal to tank pressure during explusion

MAJOR RESULTS. - The capability of Equation 1 to predict accurate total pressurant
requirements, w_p, over the range of application (Table 1) was demonstrated by close
agreement between experimental and theoretical results (Figures 1 and 2).

Table 1. Ranges of Variables Covered in Computer Program

Variable	Range
Spherical tank diameter	5–30 ft
Ellipsoidal tank diameter	5–30 ft
Cylindrical tank diameter	4–35 ft
Wall thickness	0.1–1 in.
Ratio of pressurant inlet temperature to propellant saturation temperature	2–15
Total outflow time	200–500 sec
Ambient heat flow	0–10,000 Btu/ft²-hr

Table 2. Constants for Use in Equation (1)

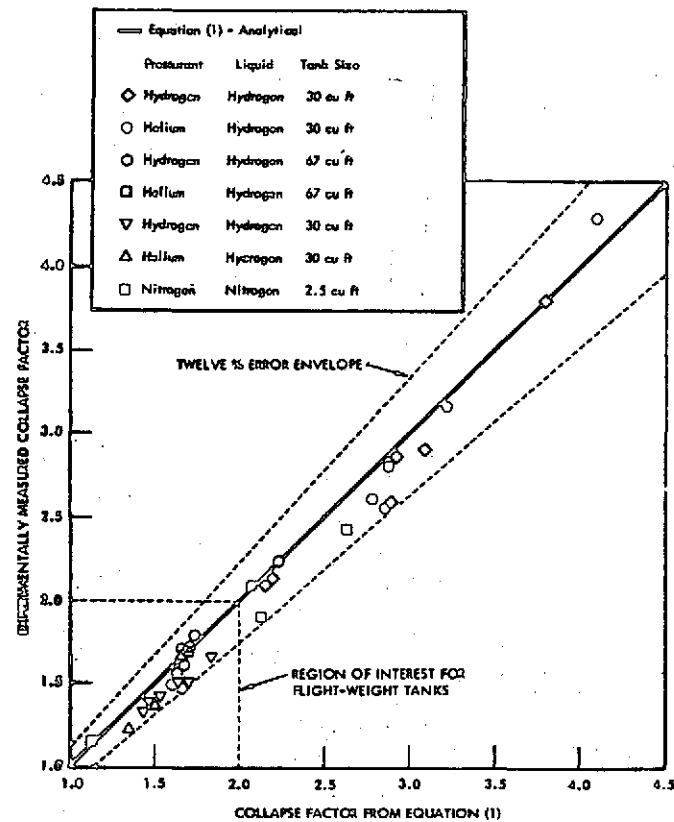| Pressurant	Propellant	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
H_2, He	H_2	0.330	0.281	4.26	0.857	1.50	0.312	0.160	0.986
O_2, N_2, He	O_2	0.775	0.209	3.57	0.790	0.755	0.271	0.236	0.895
N_2 He	N_2	↓	↓	↓	↓	↓	↓	↓	↓
F_2, He	F_2	↓	↓	↓	↓	↓	↓	↓	↓

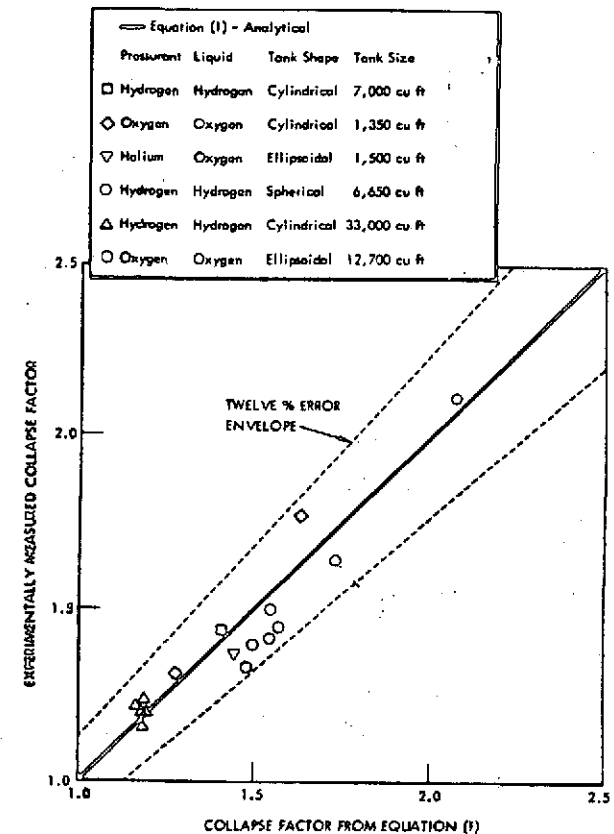Figure 1. Comparison of Predicted Cryogenic Pressurant Requirements with Data from Small Cylindrical Tanks

Figure 2. Comparison of Predicted Cryogenic Pressurant Requirements with Data from Flight-Size Tanks

EXPERIMENTAL AND ANALYTICAL STUDIES OF CRYOGENIC
PROPELLANT TANK PRESSURANT REQUIREMENTS, Nein,
M. E., Thompson, J. F., NASA-MSFC, TN D-3177,
February 1966

OBJECTIVE. - Develop accurate methods for prediction of pressurization gas require-
ments for cryogenic propellant tanks.

PERTINENT WORK PERFORMED. - A long series of experiments was conducted at
NASA-MSFC using five basic tank configurations; (1) Saturn I, S-I stage with five
interconnected LOX tanks (L/D = 7), with one having a diameter of 105-in. and four
having diameters of 70-in, (2) Saturn I, S-IV stage, spherical LOX and cylindrical
LH_2, 260-in. dia tanks, (3) 6.5-ft dia by 39-ft long cylindrical LOX tank, (4) 13-ft
dia by 26-ft long cylindrical LOX tank, and (5) 1-ft dia by 3-ft long cylindrical LOX
tank. Tank pressures and in most cases internal fluid temperatures were measured.
For the LOX tank cases, pressurization was either with GN_2, GO_2, or He. Sloshing
of tank configurations 3, 4 and 5 was also accomplished.

The analytical model used to correlate the test data was developed at Rocketdyne for
the Saturn II vehicle (Epstein and Georgius, 1964). Pertinent elements are illustrated
in Figure 1. Pressurization can either be with evaporated propellant and/or a non-
condensable gas. The ullage gas temperature, composition, and properties are
considered functions of time and of axial, but not radial or circumferential, distance.
The tank and fluid can be divided into a large number of horizontal nodes. The
experimental data was used to obtain empirical coefficients required in the program,
as well as to define modifications which were made in the methods of handling fluid-
wall and gas-liquid heat transfer and gas-liquid mass transfer.

MAJOR RESULTS. -

1. Prepressurization with helium reduces pressure decay during liquid sloshing
   near the critical frequency (Figure 2). It is assumed that helium acts as a buffer
   between the splashing liquid and condensable pressurant.

2. Under normal conditions helium pressurant must be introduced into a tank at a
   temperature 1.1 times higher than GO_2 to obtain the same ullage mean temperature.

3. The S-II computer program, as modified and utilizing recommended coefficients,
   can predict total and transient pressurant requirements and ullage temperature
   gradients within ±5%. A typical comparison is presented in Figure 3.

4. No significant radial ullage temperature gradient occurs, even in tanks with anti
   slosh baffles, and the strongest influence on pressurant weight is exerted by
   pressurant inlet temperature, for which no diminishing return occurs within a
   temperature range compatible with common tank materials.
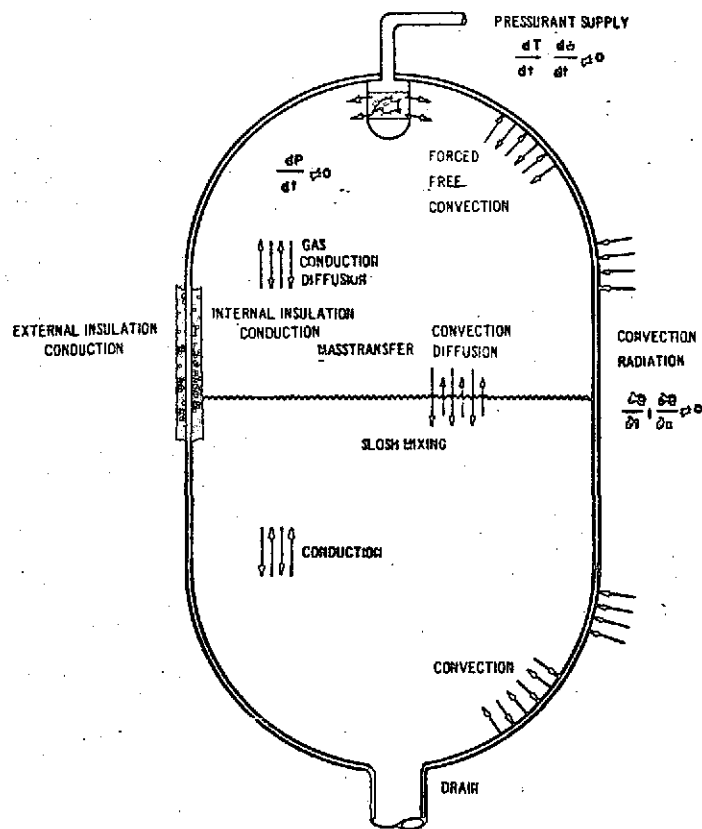
Figure 1. Pertinent Computer Program
Elements
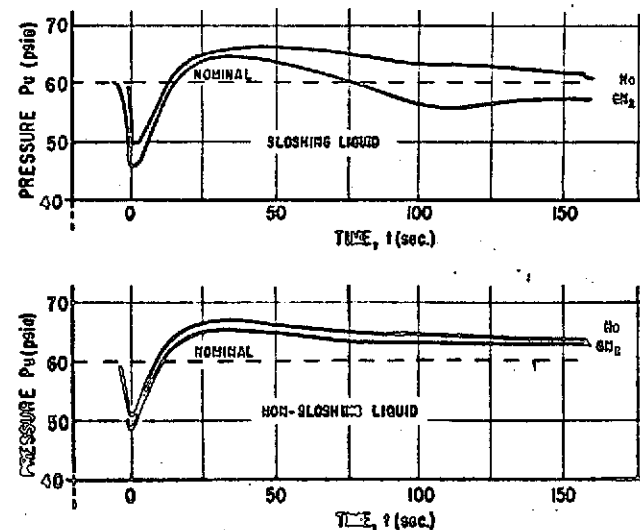
Figure 2. Comparison Between Ullage Pressure Loss For
He and GN$_2$ Prepressurants Under Liquid Slosh and
Non-Slosh Conditions in Tank Configuration 3
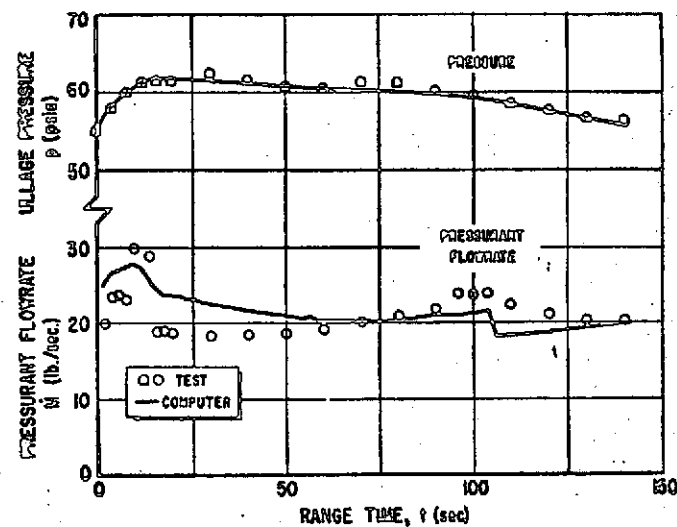
Figure 3. Comparison Between Experimental and Computed
Pressurant Flowrate, S-I Stage LOX Tank
Flight Test, Oxygen as Pressurant

7.0 VENT SYSTEMS

Covering analysis, design, fabrication and test of systems
to vent and/or control fluid storage and/or receiver tank
pressures at low-g.

LIQUID PROPELLANT THERMAL CONDITIONING SYSTEM
TEST PROGRAM - FINAL REPORT
Bullard, B.R., LMSC, NASA CR-72971, NAS3-12033, July 1972

OBJECTIVE. - To thoroughly evaluate performance of the zero-g hydrogen tank vent
system previously developed under Contract NAS3-7942 (Sterbentz, August 1968).

PERTINENT WORK PERFORMED. - Both analysis and 1-g testing were accomplished;
(1) Full scale testing in H_2 in two different size tanks (41.5 inch sphere and 100 inch
$\sqrt{2}$ oblate spheroid), (2) development of analytical models to correlate the test data,
(3) small scale testing with methane, Freon, LN_2 and LH_2 and associated analysis
of condensation at a moving liquid/vapor interface, and (4) definition of flight testing to
verify system performance. Fluid mixing was evaluated by the time to reduce tank
pressure to equilibrium, with and without venting, following pressurization with H_2
gas or with helium, each at 140°R and 530°R. Pressure was increased from 17 to 28
psia or 17 to 36 psia prior to mixing. Ability to maintain mixed fluid conditions was
evaluated by comparing pressure change rates at equilibrium with those calculated from
Equ. 1, Table 1. In addition to tank size, tank pressure and pressurant, the parameters in
Table 2 were varied. A total of 732 tests were accomplished in 1500 hours of testing.
Test plans for the 110 inch tank included television coverage of fluid circulation, but
the camera did not work, with reasons not given. Testing was also accomplished in the
110 inch tank for configurations (3) and (4), Table 2, to simulate the effect of vapor which
could be trapped at a ring baffle. This was accomplished using a series of 12 boxes
attached to a ring in the tank.

MAJOR RESULTS. -

1. Greater mixer flow was required to mix with side mount than with bottom mount.
    In the 41.5 inch tank, 20 to 30% of the liquid must be circulated for bottom
    mounting and 80 to 90% for side mounting. In fact in the 110-in. tank side mount,
    at the low flow, no pressure control could be accomplished, with and without the
    crossover duct. Using similarity relationships and experimental data, mixing
    time was found to be inversely related to the jet momentum, and is predicted to
    be directly proportional to acceleration (Equ. 2, Table 1).

2. Depressurization rates from mixing alone are significantly reduced when helium
    is present (Figure 1). However, following complete mixing, helium appears to
    have no effect on the vent down rate.

3. A theory previously developed (Sterbentz, Aug. 1968) for condensation at a moving
    liquid-vapor interface appears to have included the proper variables and parameter
    groupings (Equ. 3, Table 1).

COMMENTS. - The final form of the mixing time equation (Equ. 2, Table 1) appears
to be more empirical than analytical and correlation with test data using other fluids
and other tank shapes would be required to develop confidence in its use. Even though
performance evaluation of a zero-g vent system was the objective, only 1-g testing was
accomplished.

Table 1. Pertinent Equations

$$\frac{dP}{d\theta} = \frac{1.25\,[Q_o - (M_o\,\lambda - 3.41P)]}{\rho_L\,V_T\,(1-V_u/V_T)}\left[\frac{1}{1+\dfrac{0.36\,(V_u/V_T)}{\rho_L(1-V_u/V_T)}}\right] \qquad (1)$$

Good for H_2 only (Basic report contains derivation which could be applied to other fluids).

$$t_m\,\frac{(A_s/V_u^{2/3})\,A_j^2}{V_T\,(V_u/V_T)} = .52\,^*g\,(1/u_j)^2 \qquad (2)$$

$$Nu = C_1\,(Re\,Pr\,N_\lambda)^{1/2} \qquad (3)$$

where

P	= pump power, watts	g	= appears to be a ratio of local acceleration to acceleration at 1g or $g = a/g_c$, however, the origin of this term in the equation is not made clear in the derivation
M_o	= vent flow rate, lb/hr		
λ	= latent heat of vaporization Btu/lb		
Q_o	= external heating, Btu/hr	Nu	= Nusselt No. = $h_m L/k_L$
ρ_L	= liquid density, lb/ft^3	h_m	= condensation heat transfer coefficient
$dP/d\theta$	= differential pressure change per unit time, psi/hr	L	= length of condensing surface
V_u	= ullage volume, ft^3	Re	= Reynolds No. = $\rho_L u_o L/\mu_L$
V_T	= total tank volume, ft^3	Pr	= Prandtl No. = $\mu_L\,C_{P_L}/k_L$
t_m	= mixing time, sec	N_λ	= zero-gravity condensation No. = $\lambda/(C_{P_L}\,\Delta T)$
A_o	= liquid vapor interface area, ft^2	ΔT	= temperature difference between liquid and vapor
A_j	= area of jet exit, ft^2	u_o	= liquid velocity at interface
u_j	= liquid velocity at jet exit, ft/sec	C_1	= constant derived from theory equal to 1.12 (Ref. Sterbentz 1968 However, from tests presented in current report $C_1 \cong 0.2$

* To reproduce the correlation presented in the report (pg 151) it appears that this term should be $(.52)^2$ rather than .52.

Table 2. Test Conditions

General

Mixer Flowrates - 2.5, 3.5 and 5.5 CFM
Vent Flowrates - 0, 1.5, and 2.5 LB/HR
Ullage Volumes - 5, 25, 70 and 85%

41.5-in. Tank

Vent System Location/Mixer Orientations

(1) On Tank Bottom with Mixing Jet Directed at L/V Interface
(2) On Side of Tank with Jet Directed Across Tank at the Centerline.

External Heating - 124 to 170 Btu/hr

110-in. Tank

Vent System Location/Mixer Orientation -

(1) and (2) same as for 41.5-in Tank
(3) Side Mounted with a Duct to Distribute the Jet to the Other Side of the Tank
(4) Same as (3) except Radial Inlet Nozzle Added to Insure Taking Fluid from Along Tank Wall

External Heating - 185 to 218 Btu/hr.

Figure 1. Comparative Effect of Pressurant on Tank Pressure Response at 70 Percent Ullage –41.5 in. (1.05 cm) Tank

7-3

IN-SPACE PROPELLANT LOGISTICS
Sexton, R. E., et al, NAR, SD 72-SA-0053,
NAS8-27692, June 1972

OBJECTIVE. - Definition of a representative in-space propellant logistics system and its operation.

PERTINENT WORK PERFORMED. - Work included determination of in-space propellant requirements in support of the NASA space program plan (Fleming Model), definitions of propellant logistics system concepts to meet these requirements, cost analyses and maintenance, and manned support requirements analysis. This work is reported in five volumes; (1) executive summary, (2) technical report, (3) trade studies, (4) project planning data, and (5) cost estimates. A systems safety analysis was also accomplished and is reported in another three volumes under report number SD 72-SA-0054.

In general, the work reported here is based on existing technology or work which is summarized elsewhere. However, a few pertinent notes of current interest are presented below.

MAJOR RESULTS. -

1. The connected ullage concept shown in Figure 1 was selected as the baseline system for receiver tank thermodynamic control on the basis of minimum propellant loss, system simplicity, and compatibility with the expulsion subsystem selected. Liquid acquisition is accomplished with linear acceleration.

2. Pullthrough data developed in another study (Chen and Zukoski, 1968) was used to compare a variety of tank outlet shapes. Residuals versus Froude number are shown in Figure 2 for various tank geometries. Data from Chen and Zukoski, 1968, indicated that residuals would be two to four times greater than predicted by Berenyi and Abdalla, 1970. The selected configurations employed flow rate throttling of 10:1 to reduce residuals.

COMMENTS. - Chen and Zukoski, 1968, was not obtained in time to be included in the literature review.

Figure 1. Connected Ullage

Figure 2. Residual Versus Froude Number for
Various Tank Geometries

RESEARCH AT STANFORD ON THE CONTAINMENT OF LIQUID
HELIUM IN SPACE BY A POROUS PLUG AND ON A LONG
HOLD-TIME DEWAR FOR THE GYRO RELATIVITY EXPERIMENT
Lipa, J.A., et al, Stanford Univ., Proceedings of Cryogenic Workshop,
NASA-MSFC, March 1972

OBJECTIVE. - To develop a porous plug for zero-g venting of superfluid liquid helium.

PERTINENT WORK PERFORMED. - A porous plug was formed from a tightly wound
roll of 0.5 mil aluminum foil, the mean spacing between layers being about 10,000
angstroms. The plug was sealed between the helium chamber and an exhaust line
leading to vapor-cooled shields (Figure 1). Under a pressure difference, superfluid
helium (below 2.17K) flows through the pores of the plug and evaporates, causing
refrigeration which cools the dewar by means of the high thermal conductivity of the
plug. During test, stable operation was achieved with the dewar in both upright and
inverted positions, without appreciable variation in boiloff rate. Figure 2 shows
predicted and observed operating curves for the system in the upright position, the
temperature being varied by an auxiliary heater. The unstable regime was found to
set in at 1.8K rather than around 2.1K as expected. This was most likely due to an
inaccurate estimation of critical velocity which arose from assuming a uniform spacing
between layers.

MAJOR RESULTS. -

1. A unique, porous plug device was developed and successfully demonstrated, which
   separates helium gas and liquid phases under zero-g conditions.
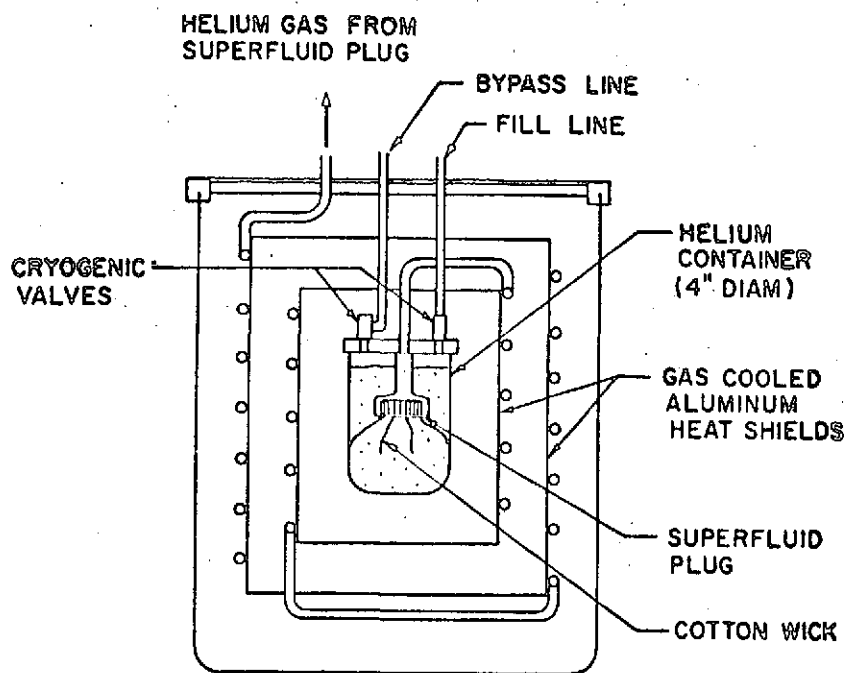
Figure 1. Cross-Section of Invertible Dewar
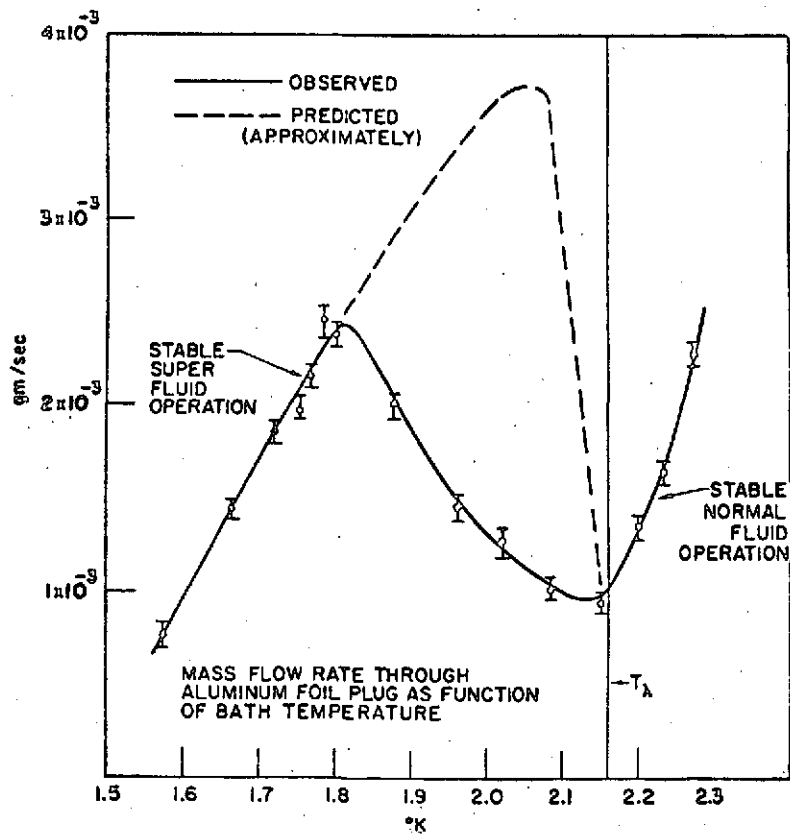
Figure 2. Flow Data for the Porous Plug

VENT FREE FLUORINE FEED SYSTEM ANALYSIS
Page, G.R., Tegart, J.R., MMC, AFRPL-TR-69-200,
F04(611)-69-C0033, September 1969

OBJECTIVE. - To perform thermodynamic simulation tests and to update an existing analytical model for conducting preliminary design analyses of space vent-free cryogenic storage systems.

PERTINENT WORK PERFORMED. - A previous contract (Murphy and Rose, 1968) investigated techniques for utilizing vented hydrogen to cool and maintain a no-vent condition in a fluorine tank during long duration space missions. To verify the analytical model a liquid hydrogen and liquid nitrogen (simulating liquid fluorine) test article, shown schematically in Figure 1, was produced. A vent heat exchanger system representative of an airborne design consisted of 13 ft of copper tubing inside the 4-ft diameter, spherical LH_2 tank, 50 feet silver brazed to the outside of the stainless steel LH_2 tank, and 50 ft brazed to the 3-ft diameter LN_2 tank. Both tanks were blanketed with one inch of aluminized Mylar/nylon net multilayer insulation. The test program was designed to generate similar thermodynamic processes at conditions that were as close as possible to those expected on an actual flight system.

The most significant test was a 34-hour run which demonstrated the feasibility of the vent heat exchanger system. During two periods of operation at a venting rate of 0.4 lbs/hour, the hydrogen tank pressure fell at the rate of 8 and 4 psi per hour, respectively, and the nitrogen pressure dropped at the rate of 2.5 and 1.7 psi per hour, respectively. The test demonstrated that for representative venting rates a significant decrease in hydrogen and nitrogen pressures can be obtained.

MAJOR RESULTS. -

1. The vent-free cryogenic storage system was shown to be feasible.

2. The potential for using a wall exchanger vent system to control H_2 tank pressure was demonstrated.

COMMENTS. - The major problem with demonstrating low-g performance of a wall exchanger system at 1-g is the differences in heat transfer coefficients and the fact that the liquid and vapor are in fixed locations at 1-g. These problems were not addressed by the work presented here.
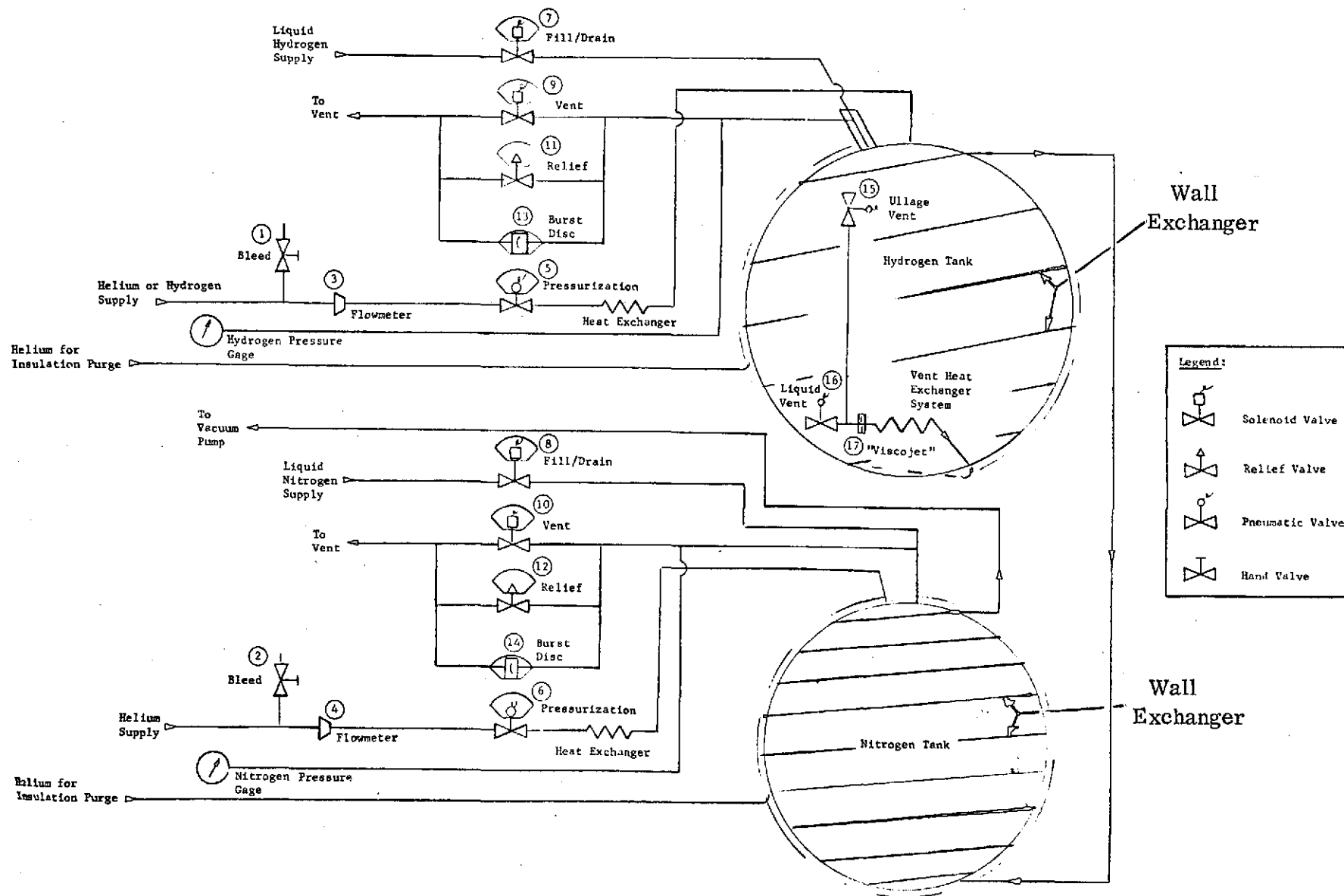
Figure 1. Propellant System Schematic

ANALYSIS OF ZERO GRAVITY RECEIVER TANK VENT SYSTEMS
Stark, J.A., Blatt, M.H., GD/C, GDC-DDB69-001, NAS8-20146, July 1969

OBJECTIVE. - To define and design an optimum vent system for use in an orbital propellant transfer receiver tank at low gravity.

PERTINENT WORK PERFORMED. - Comparisons were made of bulk heat exchanger, surface tension, mechanical separator, wall-mounted heat exchanger, and mechanical separator/wall-mounted heat exchanger combination systems for venting a 0.99 M^3 (35.2 ft^3) aluminum receiver tank. Weight, reliability, and cost data was generated. Weight data was generated for hydrogen qualities from 0.1 to 0.9 during chilldown, and for ten transfers including nine chilldowns, from 190.9K (325 R) and one from 250K (450R), Figure 1. Data was also generated for a single transfer (Figure 2). The wall heat exchanger was analyzed in more detail to determine thermal performance during chilldown. A review of film and transition boiling heat transfer data was made (Figure 3) to obtain the most accurate data for a computer program used to calculate temperatures during chilldown. Three basic configurations were analyzed for a cylindrical hemispherically ended tank; exchanger coils closely spaced on the tank cylinder, evenly distributed over the cylinder and distributed over the upper dome and cylinder. In addition to receiver venting studies, a bulk heat exchanger vent system was designed for supplying vapor to a partial reliquefaction system under development by MSFC.

MAJOR RESULTS. -

1. The mechanical separator has the best potential for achieving receiver tank venting where qualities above 0.1 are present at the vent. At the end of fill, when the quality may be below 0.1, the tank should be locked up and the pressure allowed to rise with subsequent ventdown through the low-flow orbital heat exchanger system. Design of a mechanical separator proceeded to receipt of vendor quotes.

2. For a wall exchanger, distribution over both the dome and cylindrical sections is required; tank surface area in contact with the vent gas should be at least 50%. For the single chilldown, added weight of a wall exchanger was only slightly less than the savings in vented propellant (Figure 1). For the multiple-transfer case, the net weight savings was significantly greater (Figure 2).

3. Bulk heat exchanger integration with the reliquefaction system resulted in a bulk exchanger weight of 5.66 kg (12.5 lb.) with a regulated inlet pressure to the exchanger of 163,000 ±8,950 N/M^2 (23.7 ± 1.3 psia) for a vent flow rate of 4,900 kg/sec. (3.0 lb/hr).

COMMENTS - It is noted that the receiver data was based on relatively high flow rates [0.75 kg/sec. (10 lb./min.)] without consideration of inlet flow baffling.

Figure 1. Comparative system data — vent inlet quality 0.1.

	Bulk Heat Exchanger A	Surface Tension (Complete Containment) B	Surface Tension (Local Containment) C	Mechanical Separator D	Wall Exchanger (Full Throttling, Without Pump) E	Wall Exchanger (Full Throttling, With Pump) F	Wall Exchanger (Total Throttling, Without Pump) G	Wall Exchanger (No Throttling) H	Mechanical Separator/Wall Exchanger I
Total Hardware Weight, lb	148.2	82.6	15.4	31.4	154.0	181.2	256.0	135.4	82.6
Total Chilldown Loss, lb	372.0	259.1	210.8	359.0	125.0	134.5	275.0	125.0	96.5
Total Fill Loss, lb	19.0	18.8	18.6	28.0	19.0	19.0	19.0	19.0	28.0
Total Chill Plus Fill Losses, lb	391.0	277.9	229.4	387.0	144.0	153.5	294.0	144.0	124.5
Total Weight, lb	539.2	360.5	244.8	418.4	298.0	334.7	550.0	279.4	206.9
Relative Reliability, Failures × 10⁻⁶	885.94	1519.86	947.47	717.79	714.9	972.48	654.10	883.71	732.09
Relative Cost; Lowest Cost = 1	(2.8)	(3.1)	(1.0)	(2.8)	(2.7)	(3.1)	(2.3)	(1.4)	(3.1)
Tank Volume Displaced, ft³	5.5	0.05	-	0.05	4.7	4.75	9.0	4.5	2.3

Figure 2. Comparative system data — vent inlet quality 0.1, single transfer.

	Bulk Heat Exchanger A	Surface Tension (Complete Containment) B	Surface Tension (Local Containment) C	Mechanical Separator D	Wall Exchanger (Full Throttling, Without Pump) E	Wall Exchanger (Full Throttling, With Pump) F	Wall Exchanger (Total Throttling, Without Pump) G	Wall Exchanger (No Throttling) H	Mechanical Separator/Wall Exchanger I
Hardware Weight, lb	74.1	41.3	7.7	15.7	77.0	90.6	128.0	67.7	41.2
Chilldown Loss, lb	62.8	43.1	35.7	61.0	18.5	19.9	39.4	16.5	14.3
Fill Loss, lb	4.3	3.4	3.4	5.0	4.3	4.3	4.3	4.3	5.0
Chill Plus Fill, lb	67.1	46.5	39.1	66.0	22.3	24.2	43.7	22.3	19.3
Total Weight, lb	141.2	87.8	46.8	81.7	99.8	114.8	171.7	90.5	60.5

Figure 3. Film boiling heat transfer coefficients.
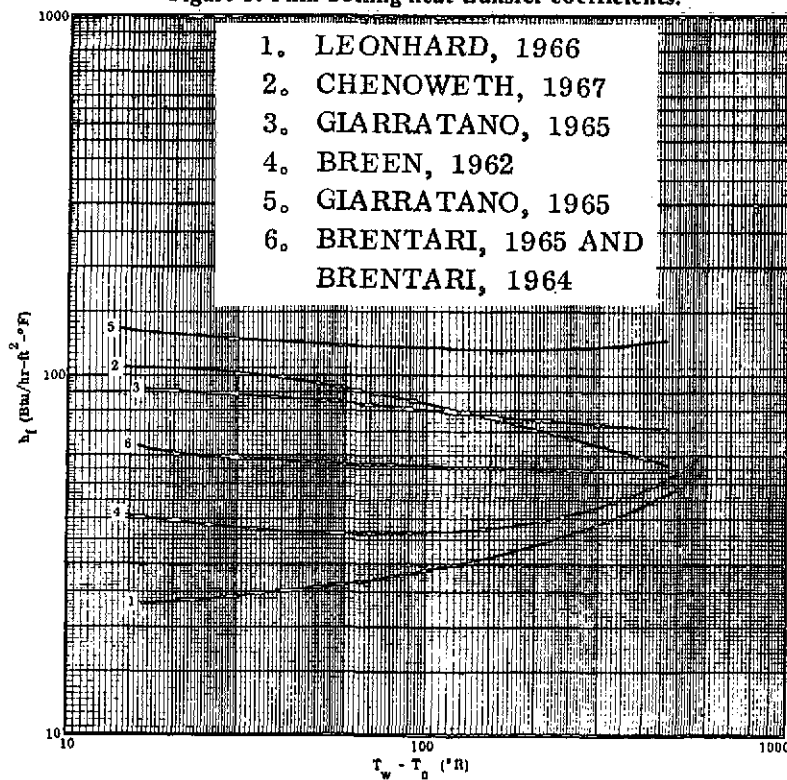
1. LEONHARD, 1966
2. CHENOWETH, 1967
3. GIARRATANO, 1965
4. BREEN, 1962
5. GIARRATANO, 1965
6. BRENTARI, 1965 AND BRENTARI, 1964

ZERO-GRAVITY TEST OF AN ADVANCED SURFACE-TENSION
PROPELLANT ORIENTATION AND ULLAGE VAPOR VENTING DEVICE
Bovenkerk, P.E., USAF, AFRPL-TR-69-119, June 1969

OBJECTIVE. - To determine the functional capabilities of a representative liquid
propellant surface tension orientation and vapor venting system.

PERTINENT WORK PERFORMED. - The system configuration tested resulted from
analysis, 1-g tests and trade-offs conducted under Contract AF 04(611)-9901 (Boraas,
et al, 1965). This device (Figure 1) uses a plain "pie pan" screen (1), as the con-
tainment device. A vent region is between the contoured baffle (2) and the inner
wall of the tank. When direct venting takes place, such as when gas is located at (a),
it is via the screened holes at (3), the circumferential openings in the baffle (4), and
the screened openings (5). The screens at (3) are designed to prevent liquid from
entering the contoured passage during non-vent conditions. When gas is not at (a)
while venting, liquid at (3) will be drawn into the contoured passage. This passage is
designed to prevent liquid from reaching the screens at (5), however, should this occur
accidentally, the screens at (5) are of high solidity to keep liquid out of the small
chamber (6) under all conditions. This chamber (6) then serves as a source of liquid-
free gas. The standpipe (7) is designed to increase the amount of time that direct gas
venting is possible. The plate (8) functions as a capillary to retain some liquid above
(1) to insure good liquid-to-liquid contact across the containment screen (1). The
containment and vent screens are 200 × 200 mesh. Testing was accomplished using
a KC-135 aircraft operating at low-g (free floating capsule) for periods of 3 to 15 sec.
The test tank was a 12-in. diameter transparent sphere. The test fluid was a solution
of water and isopropyl alcohol. A total of 120 maneuvers were accomplished, however,
they all did not provide acceptable zero-g time. Fluid behavior, fluid expulsion and
vapor venting tests were conducted at fill levels of 80, 50, 30 and 10%.

MAJOR RESULTS. -

1. The use of surface-tension screens for liquid orientation was successfully
   demonstrated.

2. Liquid free venting was accomplished, indicating that capillary traps can be utilized
   to increase the effectiveness of the vent. However, for these tests the vent rate and
   volume of gas to reduce tank pressure was extremely low and since there is no means
   of insuring that the underside of the vent baffle will not be covered with liquid
   successful operation is very mission dependent. Also there is no way of guaranteeing
   that the vent baffle screen will remain wetted throughout a mission and there is the
   possibility of forcing some liquid through the vent on every vent cycle. Therefore,
   without total liquid orientation, efficient venting is based only on probability.
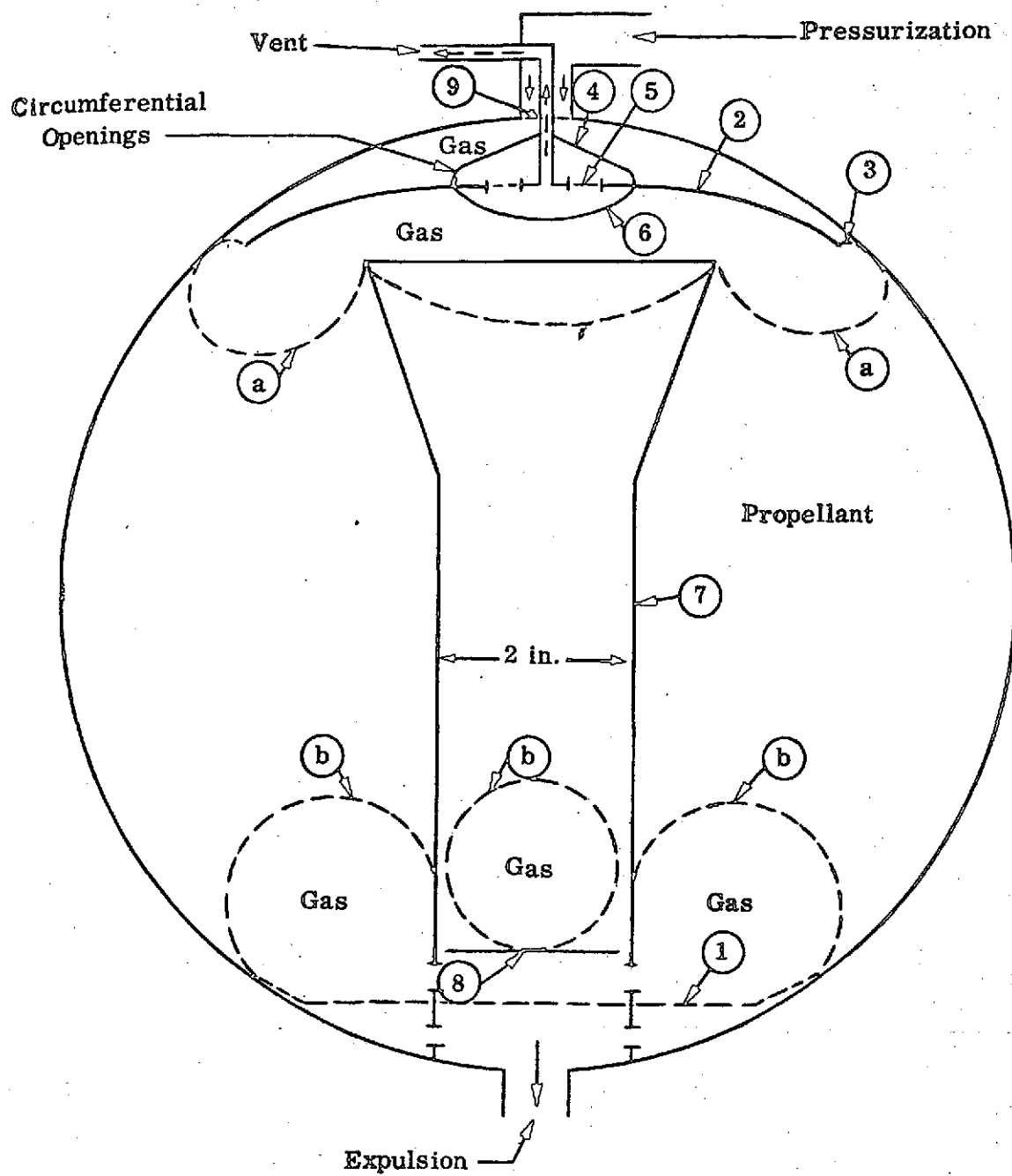
Figure 1. Test Model Configuration E

LIQUID PROPELLANT THERMAL CONDITIONING SYSTEM —
FINAL REPORT
Sterbentz, W. H., et al, LMSC, NASA CR-72365, NAS3-7942,
August 1968

OBJECTIVE. - To develop and demonstrate the effectiveness of a liquid propellant
thermal conditioning type low-g vent system to control cryogenic H_2 tank pressure.

PERTINENT WORK PERFORMED. - The subject vent system operates by throttling
the vent fluid to a low pressure and temperature to exchange heat with the bulk tank
fluid to vaporize any liquid present at the vent inlet. Such a system can thus vent va-
por even though the inlet is 100% liquid. Initially, parametric weight and perform-
ance data were generated for the individual system components; fluid removal unit
(liquid only, liquid-or-vapor), expansion valve, heat exchanger (compact and wall
types), mixer (electric drive, AC and DC and turbine drive), and pressure switch.
Comparisons were made and optimum systems defined for the H_2 tanks on three dif-
ferent vehicles; (1) Earth/Lunar logistics, 134 days coast, (2) Earth/Mars Kickstage,
220 days, and (3) Earth/Mars manned, 220 days. Details of this work are presented
in an interim report (Sterbentz, et al, 1967). The resulting system is illustrated in
Figure 1. For the vent system to properly control tank pressure, any bulk liquid
cooled within the exchanger must be thermally mixed with the ullage vapor. Fluid
mixing 1-g testing was accomplished using a two-dimensional flow setup (closely
spaced horizontal transparent plates in the form of a circle). A full-scale vent sys-
tem design was generated for the vehicle (2) requirements, hardware fabricated and
1-g testing accomplished. A brushless DC motor was recommended for the pump
drive, but since none were available for H_2 service, an AC motor was used in the test.
Pertinent system design characteristics are presented in Table 1. The major testing
was accomplished in a 110-in.-dia. oblate spheroid tank with the vent package at two
different locations; (1) suspended 15 in. from the top (mixer flow directed down), and
(2) at the tank side (mixer flow across tank centerline). Testing was accomplished
with the top mount at H_2 ullage volumes of 5 and 50% and at 5, 27, 50, and 75% ullage
with the side mount. The package was instrumented with temperature and pressure
probes but bulk fluid stratification was not determined.

MAJOR RESULTS. -

1. The vent system as designed and built controlled tank pressure efficiently in a
   110-in.-dia. H_2 tank whether immersed in gas or liquid, and there was no discern-
   ible difference in performance whether the mixing flow was in the same direction
   or perpendicular to the gravity vector. Typical pressure control is illustrated in
   Figure 2.

2. From the two-dimensional testing, the critical Weber number for a jet ($\rho U_j^2 D_j/\sigma$) to
   circulate liquid around a spherical tank = $4(1 + 0.16 H/D_j)$ where H is distance from
   the jet nozzle to the opposite tank wall.

Table 1. Pertinent System Operating Parameters

External Heating = 11.5 Btu/hr nominal

Vent Cycle = On-off with vent flow of 1.4 lb/hr.

Inlet Pressure Range = 17 to 28 psia with nominal control
to 18 ± 1.2 psia.

System Weight = 15 lb

Exchanger Vent Pressure = 4 ± 0.4 psia

Mixer Design Exit Velocity = 5 ft/sec
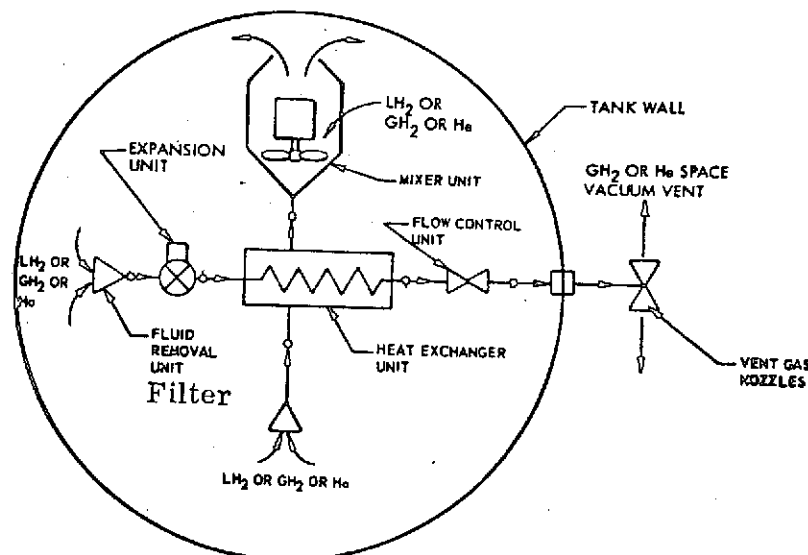
Figure 1. Selected Liquid Propellant Thermal
Conditioning System Schematic
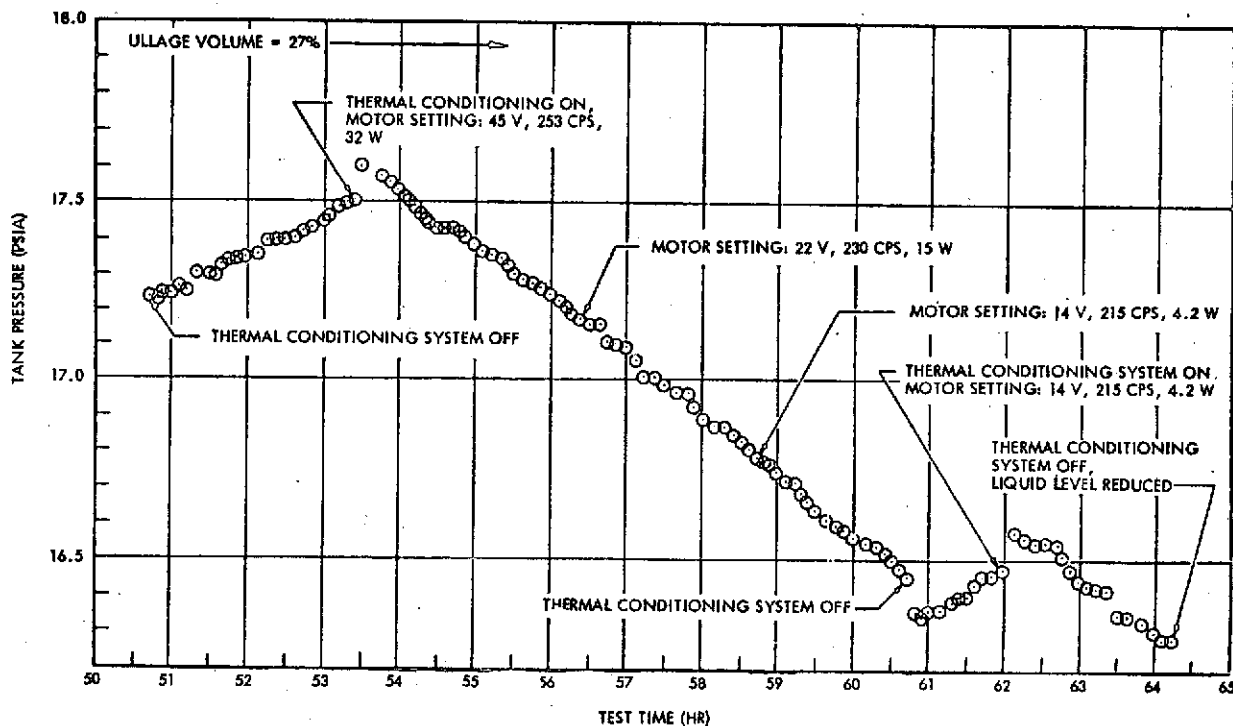
Figure 2. "110-in. dia. Tank, Unit-Side Mounted, Submerged in Liquid"

SUBCRITICAL CRYOGENIC STORAGE DEVELOPMENT
AND FLIGHT TEST
Allgeier, R.K., NASA-JSC,TN D-4293, February 1968

OBJECTIVE. - To design and fabricate operational subcritical cryogenic storage systems for ground test (Phase I), and to evaluate the performance of follow-on subcritical hardware in earth orbit (Phase II).

PERTINENT WORK PERFORMED. - Operational concepts for the storage of subcritical cryogenic fluids and the delivery of single-phase (vapor) were developed. During Phase I two subcritical systems were fabricated by AiResearch and tested which employed regenerative heat exchangers for pressure control and electrical heaters for rapid depletion. A capacitance gage matrix was installed in the tanks for fluid quantity measurements. Thermodynamic and vibration tests of the Phase I devices indicated that the concept warranted verification in a low gravity environment.

The Phase II subcritical storage and supply system (Figure 1) was a self-contained package having all components necessary to store liquid nitrogen for extended periods and deliver the vapor phase under the environmental conditions of orbital flight. The tank was a spherical dewar on the order of 25 inches inside diameter. Two systems were fabricated, one for orbital evaluation and the other for qualification testing and flight system backup. An electrical heater was used to replace the regenerative heat exchangers to minimize system complexity. The system was flown aboard Apollo Mission AS-203 in July 1966. It exhibited good pressure control and stability, and the heat exchanger outlet temperature and the delivery temperatures were significantly above saturation. The capacitance gage successfully monitored the quantity of fluid in the tank throughout the test.

MAJOR RESULTS. -

1. A flightweight, subcritical cryogenic storage system was designed, fabricated and successfully tested in earth orbit.

2. This was the first successful orbital test of a three-dimensional wire matrix mass gaging device.

3. Single-phase vapor was consistently delivered by the system throughout the test.

Pressure switch

Safety relief valve (mounted on girth ring)

P1 — Signal conditioner, pressure, P1 (mounted on girth ring)

Current monitor, I1

I1

Vent valve (capped)

Signal-conditioner plate

T2

Signal conditioner, temperature, T2

Matrix "A"   Q1

Matrix "B"

Signal conditioner, matrix, Q1

Electrical heater

Quantity-gage capacitance matrix

T1

T3

Signal conditioner, temperature, T1

Signal conditioner, temperature, T3

Fill valve (capped)

28 V dc

Ground pressurization heater

Internal pressure regulator

Signal conditioner, pressure, P2 (mounted on girth ring)

P2

Solenoid valve

P2

Absolute pressure regulator

28 V dc

FM1

Signal conditioner, flow, FM1

FM1 Flow restrictor

Ambient

P3

T5

Supply relief valve

Temperature sensor I2

Electrical heater

Warmup heat exchanger

Heater control

T4

P3

Signal conditioner, pressure, P3

Signal conditioner, temperature, T5

Current monitor, I2

Signal conditioner, temperature, T4

Design parameters

Operating pressure range	130 – 170 psia	Ambient temperature range	-65 to + 160°F
Delivery pressure	60 ± 5 psia	Delivery rate	1.25 ± .13 lb/hr
Relief pressure	220 ± 20 psia	Total electrical power available, prelaunch	28 V dc, 400W
Proof pressure	360 psia minimum		
Burst pressure	480 psia minimum	Total electrical power available, postlaunch	28 V dc, 174W
Maximum filled weight	275 lb		
Liquid nitrogen capacity	128 lb	Shelf life	1 year
Standby time, nonvented, at 160°F	30 hr	Radio noise specification	MIL-I-26600 (USAF)

Figure 1.   Phase II Subcritical Nitrogen System

ZERO GRAVITY PROTOTYPE VENT SYSTEM
Stark, J. A., Blatt, M. H., GD/C, NAS8-20146,
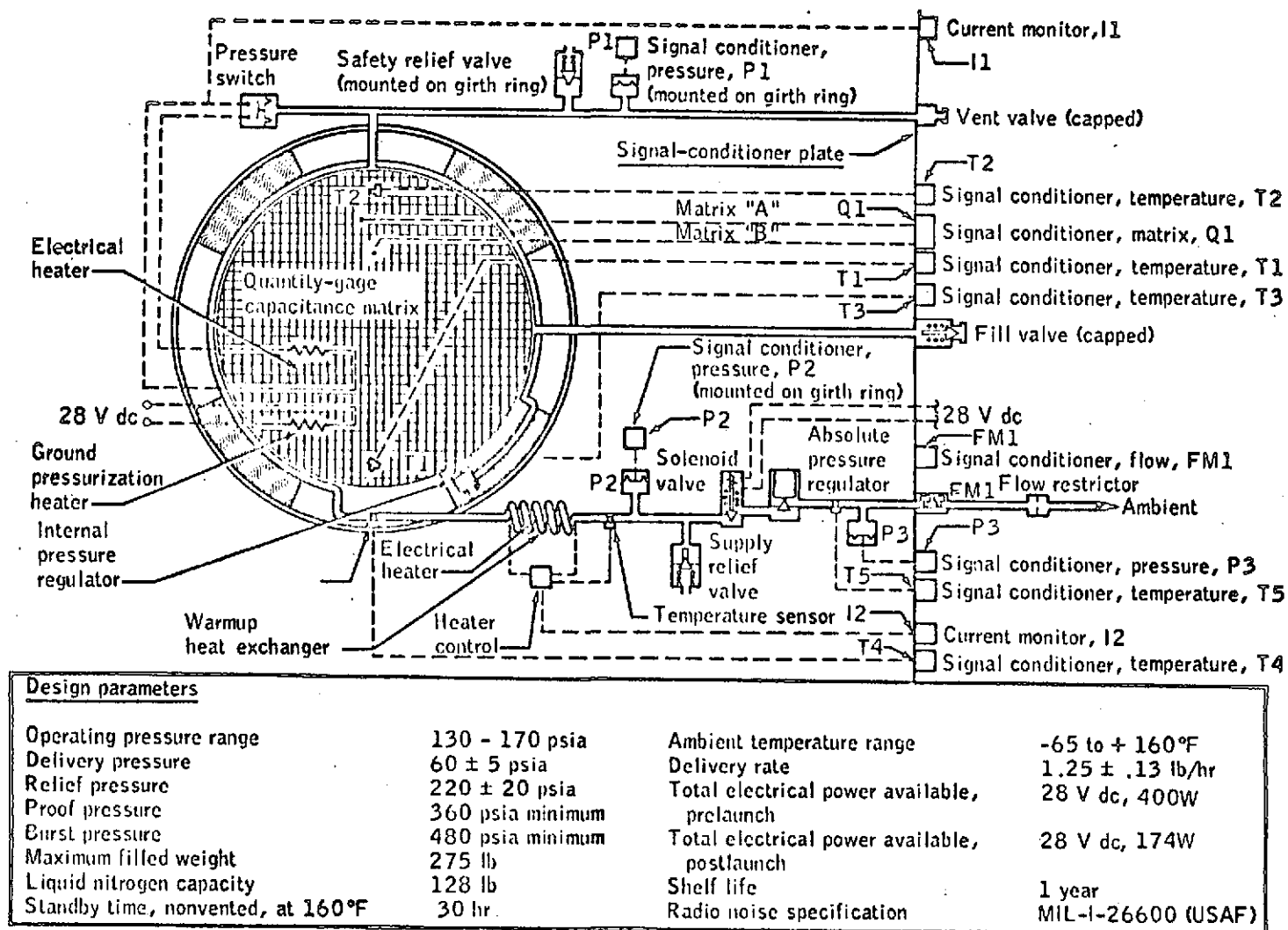GDC-DDB67-006, October 1967

OBJECTIVE. - To define, design, fabricate and test a prototype heat exchanger vent system capable of controlling tank pressure while discharging only GH_2, even though the system and/or its inlet is in 100% LH_2 as may be encountered in space at low-g.

PERTINENT WORK PERFORMED. - In the system definition phase, trade-offs were made to determine the type of heat exchange (bulk vs wall), type of pump drive (electric vs turbine), optimum vent flow rate, vent cycle, and fluid mixing criteria. Basic design requirements were to control tank pressure to 17 ± 1 psia with external heating of 20-30 Btu/hr over 14 days. The resulting system is shown schematically, as setup for test, in Figure 1. Operation is by throttling the vent inlet to a low pressure and temperature and flowing through the heat exchanger to vaporize any liquid which may be present. Operation is intermittent to minimize total pump power input to the tank. The pump provides forced convection exchanger flow as well as liquid temperature destratification. Deactuation and actuation of vent and pump are controlled by a pressure-switch. Testing was at 1-g with hydrogen in a 40-in. dia. by 84-in. long superinsulated CRES tank. The system was located 22 in. from the tank bottom and tests performed with the mixing flow (exchanger warm side outlet) directed (1) radially (2) downward and (3) upward. In each case testing was performed with the unit in vapor (13 in. LH_2 level) and liquid (49 in. and 70 in. levels). The 3-way valve (Fig. 1) provided either liquid or vapor inlet at all tank liquid levels. Both steady state and transient performance of the system was determined. In addition to the Figure 1 instrumentation, temperatures were measured throughout the tank fluid with platinum resistance sensors.

MAJOR RESULTS. -

1. Feasibility and efficiency of the concept was demonstrated. No liquid was vented under all design operating conditions. A typical tank pressure trace is presented in Figure 2.

2. Tank fluid mixing and liquid/ullage coupling were found to be important for efficient pressure control. Operation with the system in liquid and the mixing flow directed down was inefficient and in fact, at a LH_2 level of 70-in., tank pressure was not controlled (Figure 3). Flow directed at the L/V interface was best for mixing with radial flow next.

3. An apparent freezing of LH_2 in the throttle valve during one of the tests was solved by locating the shutoff valve downstream of the heat exchanger and external to the tank.

Table 1. Pertinent Vent System Characteristics

Operation Cycle - Intermittent (on 1/30th of total)
Vent Flow - 3 lb/hr
Pump Power - 7 watts
Throttling Pressure - 5 psia
Test System Wt. - 11 lb. Est. Flight Wt. - 8.2 lb
Pressure Switch - 17 ± 1 psia with 0.5 psi min. deadband

Figure 1. Basic Vent System
Test Schematic

3/8 in.
line

Figure 2. Tank Pressure (Second Test Series,
9.6 to 11.0 Hours)

Figure 3. Tank Pressure (Third Test
Series 21.5 to 22.5 Hours)

LEGEND

AL - System Actuates with
Liquid Inlet

LG - Cycled Inlet from Liquid
to Gas

GL - Cycled Inlet from Gas
to Liquid

AG - System Actuates with
Gas Inlet

STUDY OF ZERO-GRAVITY, VAPOR/LIQUID SEPARATION
Mitchell, R. C., et al, GDC-DDB65-009, NAS8-20146, January 1966

OBJECTIVE. - To define the best method(s) of separating vapor from liquid in order
to permit vapor-only venting of cryogenic propellant tanks operating at low-g.

PERTINENT WORK PERFORMED. - Analyses were accomplished and preliminary
designs were developed on four primary methods of liquid/vapor separation; (1) heat
exchange where the vent fluid is throttled to a low pressure and temperature and allowed
to exchange heat with the tank fluid to vaporize any liquid initially present in the vent,
(2) mechanical-employing a rotating element for centrifugal separation, (3) dielectro-
phoresis–utilizing an electric field to separate liquid from vapor (both total liquid
control and local separator devices were considered), and (4) surface tension-utilizing
fluid surface forces to orient the liquid in a tank with baffles or screens, or to effect
local separation at the vent. Other methods including vent fluid rotation or vortexing,
"hydrogen sublimation", and magnetic positioning were considered, but not studied
in detail or included in the predesign comparisons.

Predesigns including weights, power, reliability and pertinent operating characteristics
were generated for the four basic systems above for three vehicle/mission cases;
(1) S-IVB stage with continuous venting during a 4-1/2 hour coast with retention of the
existing settling provisions, (2) S-IVB stage without constraints and (3) a cryogenic
service module (CSM) with a multiple restart, 205 hr mission. Existing work was
reviewed and existing data used where available. Otherwise new data were generated.
In the S-IVB work only the hydrogen tank was considered, while for the CSM both
H_2 and O_2 tanks were considered, though emphasis was on the hydrogen application.

MAJOR RESULTS. -

1. It was concluded that the heat exchange system is the most promising for the three
    vehicle/mission cases considered (Tables 1 and 2). The mechanical separator was
    a close second on most of the selection criteria except performance in 100% liquid.
    The dielectrophoretic and surface tension systems were consistently poorer on all
    of the selection criteria.

2. Total liquid control by surface tension or dielectrophoresis was not competitive
    for the venting application alone, due to the high weights involved.

3. Following selection of the heat exchange system as the most promising a significant
    amount of parametric and detailed design data were generated over a wide range
    of H_2 operating conditions. Coupling of the exchanger vent with a reliquefaction
    system was also briefly considered.

Table 1. Comparison of Zero-g, Vapor/Liquid Hydrogen Separation Systems for Cases I and II (S-IVB)

CRITERION	RELATIVE RATING (Lowest Rating is Best)			
	HEAT EXCHANGE SYSTEM	MECHANICAL SEPARATOR	DIELECTRO-PHORETIC SEPARATOR	SURFACE TENSION SEPARATOR
System hardware weight (as equivalent pounds payload decrease)	78	77	197	162
Change in weight of vented propellant (as equivalent pounds payload decrease)	-11	11	11	-9
Relative system components failure rate (10^{-6} failures per mission)	307	342	527	428
Current feasibility of successful system operation (on 1 to 3 scale - not relative magnitudes)	1	2	3	3
Availability of design data (on 1 to 2 scale - not relative magnitudes)	1	1	2	2
Performance of system in 100-percent liquid (on 1 to 4 scale - not relative magnitudes)	1	2	3	4
"Complexibility" - measure of complexity of device and difficulty of development to successful operational status (on 1 to 2 scale - not relative magnitudes)	1	1+	2	2

Table 2. Comparison of Zero-g, Vapor/Liquid Hydrogen Separation Systems for Case III (CSM)

CRITERION	RELATIVE RATING (Lowest Rating is Best)			
	HEAT EXCHANGE SYSTEM	MECHANICAL SEPARATOR	DIELECTRO-PHORETIC SEPARATOR	SURFACE TENSION SEPARATOR
System hardware weight (as equivalent pounds payload decrease)	13	10	66	36
Change in weight of vented propellant (as equivalent pounds payload decrease)	2	4	79	32
Relative system components failure rate (10^{-4} failures per mission)	164	141	255	190
Current feasibility of successful system operation (on 1 to 3 scale - not relative magnitudes)	1	2	3	3
Availability of design data (on 1 to 2 scale - not relative magnitudes)	1	1	2	2
Performance of system in 100% liquid (on 1 to 4 scale - not relative magnitudes)	1	2	3	4
"Complexibility" - measure of complexity of device and difficulty of development to successful operational status (on 1 to 2 scale - not relative magnitudes)	1	1+	2	2

8.0 FLUID MIXING

Covering analysis, design fabrication and test of systems to destroy
fluid temperature stratification and/or minimize tank pressure rise
by fluid mixing.

HEATER-MIXER FOR STORED FLUIDS

Canning, T.N., NASA-Ames,U.S. Patent No. 3,782,698,
August 1972

OBJECTIVE. - Devise a system for improved mixing of stored fluids.

PERTINENT WORK PERFORMED. - The system shown in Figure 1 was conceived.
As shown in Figure 1, an auxiliary chamber is immersed in the fluid stored in a
larger fluid storage vessel. A heating element is wound on the wall of the auxiliary
chamber. The auxiliary chamber is connected in fluid communication with the main
storage vessel by means of a jet nozzle. The wall of the auxiliary chamber is heat
cycled to produce a corresponding expansion and contraction of the fluid within the
auxiliary chamber to produce heating and mixing of the stored fluid by means of jetting
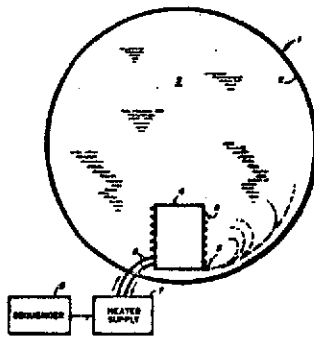the expanded fluid to and fro relative to the stored fluid contents of the vessel.

Figure 1. Thermal Fluid Mixing System

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LIQUID PROPELLANT THERMAL CONDITIONING SYSTEM
TEST PROGRAM - FINAL REPORT
Bullard, B.R., LMSC, NASA CR-72971, NAS3-12033, July 1972

OBJECTIVE. - To thoroughly evaluate performance of the zero-g hydrogen tank vent system previously developed under Contract NAS3-7942 (Sterbentz, August 1968).

PERTINENT WORK PERFORMED. - Both analysis and 1-g testing were accomplished; (1) Full scale testing in H_2 in two different size tanks (41.5 inch sphere and 100 inch $\sqrt{2}$ oblate spheroid), (2) development of analytical models to correlate the test data, (3) small scale testing with methane, Freon, LN_2 and LH_2 and associated analysis of condensation at a moving liquid/vapor interface, and (4) definition of flight testing to verify system performance. Fluid mixing was evaluated by the time to reduce tank pressure to equilibrium, with and without venting, following pressurization with H_2 gas or with helium, each at 140°R and 530°R. Pressure was increased from 17 to 28 psia or 17 to 36 psia prior to mixing. Ability to maintain mixed fluid conditions was evaluated by comparing pressure change rates at equilibrium with those calculated from Equ.1, Table 1. In addition to tank size, tank pressure and pressurant, the parameters in Table 2 were varied. A total of 732 tests were accomplished in 1500 hours of testing. Test plans for the 110 inch tank included television coverage of fluid circulation, but the camera did not work, with reasons not given. Testing was also accomplished in the 110 inch tank for configurations (3)and (4), Table 2, to simulate the effect of vapor which could be trapped at a ring baffle. This was accomplished using a series of 12 boxes attached to a ring in the tank.

MAJOR RESULTS. -

1. Greater mixer flow was required to mix with side mount than with bottom mount. In the 41.5 inch tank, 20 to 30% of the liquid must be circulated for bottom mounting and 80 to 90% for side mounting. In fact in the 110-in. tank side mount, at the low flow, no pressure control could be accomplished, with and without the crossover duct. Using similarity relationships and experimental data, mixing time was found to be inversely related to the jet momentum, and is predicted to be directly proportional to acceleration (Equ. 2, Table 1).

2. Depressurization rates from mixing alone are significantly reduced when helium is present (Figure 1). However, following complete mixing, helium appears to have no effect on the vent down rate.

3. A theory previously developed (Sterbentz, Aug. 1968) for condensation at a moving liquid-vapor interface appears to have included the proper variables and parameter groupings (Equ. 3, Table 1).

COMMENTS. - The final form of the mixing time equation (Equ. 2, Table 1) appears to be more empirical than analytical and correlation with test data using other fluids and other tank shapes would be required to develop confidence in its use. Even though performance evaluation of a zero-g vent system was the objective, only 1-g testing was accomplished.

Table 1. Pertinent Equations

$$\frac{dP}{d\theta} = \frac{1.29\,[Q_o - (M_o\,\lambda - 3.41P)]}{\rho_L\,V_T\,(1-V_u/V_T)}\left[\frac{1}{\left[1 + \dfrac{0.36\,(V_u/V_T)}{\rho_L(1-V_u/V_T)}\right]}\right] \qquad (1)$$

Good for H_2 only (Basic report contains derivation which could be applied to other fluids).

$$t_m\,\frac{(A_o/V_u^{2/3})\,A_j^2}{V_T\,(V_u/V_T)} = .52\,{}^\circ g\,(1/u_j)^2 \qquad (2)$$

$$Nu = C_1\,(Re\,Pr\,N_\lambda)^{1/2} \qquad (3)$$

where

P	= pump power, watts	g	= appears to be a ratio of local acceleration to acceleration at 1g or g = a/g_c, however, the origin of this term in the equation is not made clear in the derivation
M_o	= vent flow rate, lb/hr		
λ	= latent heat of vaporization Btu/lb		
Q_o	= external heating, Btu/hr	Nu	= Nusselt No. = $h_m L/k_L$
ρ_L	= liquid density, lb/ft³	h_m	= condensation heat transfer coefficient
$dP/d\theta$	= differential pressure change per unit time, psi/hr	L	= length of condensing surface
V_u	= ullage volume, ft³	Re	= Reynolds No. = $\rho_L u_o L/\mu_L$
V_T	= total tank volume, ft³	Pr	= Prandtl No. = $\mu_L C_{P_L}/k_L$
t_m	= mixing time, sec	N_λ	= zero-gravity condensation No. = $\lambda/(C_{P_L}\,\Delta T)$
A_o	= liquid vapor interface area, ft²	ΔT	= temperature difference between liquid and vapor
A_j	= area of jet exit, ft²	u_o	= liquid velocity at interface
u_j	= liquid velocity at jet exit, ft/sec	C_1	= constant derived from theory equal to 1.12 (Ref. Sterbentz 1968 However, from tests presented in current report $C_1 \cong 0.2$

° To reproduce the correlation presented in the report (pg 151) it appears that this term should be $(.52)^2$ rather than .52.

Table 2. Test Conditions

General

Mixer Flowrates	- 2.6, 3.9 and 5.5 CFM
Vent Flowrates	- 0, 1.5, and 2.5 LB/HR
Ullage Volumes	- 5, 25, 70 and 85%

41.5-in. Tank

Vent System Location/Mixer Orientations

(1) On Tank Bottom with Mixing Jet Directed at L/V Interface
(2) On Side of Tank with Jet Directed Across Tank at the Centerline.

External Heating - 124 to 170 Btu/hr

110-in. Tank

Vent System Location/Mixer Orientation -

(1) and (2) same as for 41.5-in Tank
(3) Side Mounted with a Duct to Distribute the Jet to the Other Side of the Tank
(4) Same as (3) except Radial Inlet Nozzle Added to Insure Taking Fluid from Along Tank Wall

External Heating - 185 to 218 Btu/hr.

Figure 1. Comparative Effect of Pressurant on Tank Pressure Response at 70 Percent Ullage - 41.5 in. (1.05 cm) Tank

STUDY OF CRYOGENIC FLUID MIXING
TECHNIQUES - FINAL REPORT
Van Hook, J.R., Poth, L.J., GD/FW, FZA-450-1, NAS8-24882,
September 1970

OBJECTIVE. - Verify the validity of utilizing small-scale-tank mixing parameters in
the design of full-scale-tank mixers and apply previously developed mixing techniques
(Poth, et al, 1968) to the design of LO_2 mixer systems.

PERTINENT WORK PERFORMED. - Mixing tests were conducted in a 10-ft-dia. by
20-ft-high tank using non-pressurized water as the test fluid. Jet mixing was employed
where liquid was taken from the bottom of the tank and introduced back into the tank
bottom as an axial jet directed at the liquid/vapor interface. The tank had a flat
bottom and open top. The data obtained consisted of temperature histories and observed
jet motion. Comparisons were made with the data from small scale tests with water
in 1-ft-dia by 2-ft-high closed (hemispherical top) tanks with concave and convex
bottoms (Poth, et al, 1968).

Hot water was used to induce stratification layers from 0.5 to 19.5-ft-thick. Jet
diameters were 0.875 and 0.625-in., as scaled up from the small-tank tests. Flow
rates were varied from 11.7 to 136.5 gpm. Data from 52 test runs are reported.
Correlations were made for three basic parameters; (1) time for jet to move from
nozzle exit to liquid surface, θ_j, (2) effects of buoyancy on mixing time, and (3) time,
after mixing begins, to reach a specified percent of the completely mixed condition.

MAJOR RESULTS. -

1. Both small and large scale data for jet transit time correlated well with the equation;
   $(V_o D_o/D_t^2) \theta_j = 0.152 (Z_b/D_t)^2$. Nomenclature are defined in Table 1.

2. Data on the effects of buoyancy on mixing time agreed with that of the small scale
   tests (Figure 1) and it is concluded that buoyancy effects can be neglected when
   predicting low-g mixing times.

3. In the large-scale tests, stratification thickness was found to be an important variable
   affecting mixing time and a different correlation was necessary to produce a good
   data grouping (Figure 2).
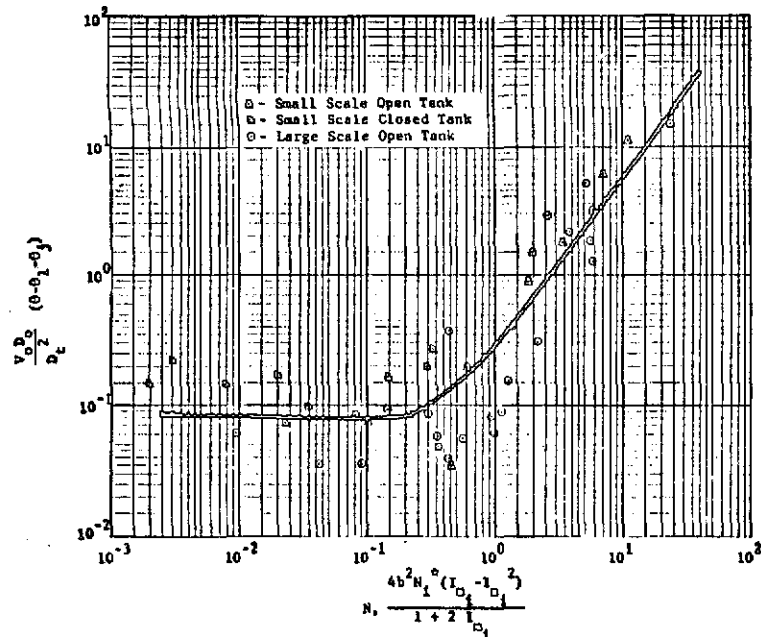
Figure 1. Effect of Buoyancy on Mixing; Large and Small Scale Water Tests

Figure 2. Correlation of the Dimensionless Time Required for Temperature Stratification or Ullage Pressure to Reach 10% of its Initial Value Versus N, Large and Small Tank Tests

V_o = nozzle exit velocity

D_o = nozzle exit diameter

D_t = tank diameter

b = constant, 0.25

$N_i^* = [a\,\beta\,(T_s-T_b)_i\,Z_b^3]/(V_oD_o)^2$

$I_{m_i} = 1 - [(T_s-T_m)_i/(T_s-T_b)_i]$

θ = time to mix after pump turned on

θ_j = jet transit time

θ_1 = time after mixing begins

T_s = liquid surface temperature

T_b = bulk temperature

T_m = mean fluid temperature

Z_b = distance from nozzle to liquid surface

Subscript

i = initial

Table 1. Nomenclature

A STUDY OF CRYOGENIC PROPELLANT MIXING TECHNIQUES

Vol. I, Mixer Design and Experimental Investigations, Vol. II,
Experimental Data, Poth, L.J., et al ,GD/FW, FZA-439, NAS8-20330
November 1968.

OBJECTIVE. - Develop technology required for prediction of thermal stratification
of cryogenic fluids at low-g and means by which equilibrium can be achieved (mixing).

PERTINENT WORK PERFORMED. - The first annual report of this contract (Poth,
Sept. 1967) selected jet mixing as the preferred type of mixing. The present is con-
cerned with application to large cryogenic vehicles. Scaling data is emphasized as
well as primary problems occurring in the application of data from one-g testing.
Various stratification models considered are illustrated in Figure 1. Extensive
consideration is given to the mixer power drive and the state-of-the-art in this field.
Mixing tests used water with dye-injection in the jet and tank temperature measurements
for 58 non-pressurized open-tank tests and only tank temperature measurements
in 20 pressurized closed tank tests. A brief bench-type study of low Bond number
mixing was also performed in small size tubes with water although modeling difficulties
occurred.

MAJOR RESULTS. -

1. Feasibility of jet mixing was established and mixing times were correlated with the
   product of fluid power times outlet diameter (Fig's 2, 3). Increased nozzle size for
   a given power reduces mixing time. Conventional vane axial pumps proved adequate,
   however fluid power available from a given pump can be doubled with a more
   efficient brushless dc motor. This motor also desirably speeds up with vapor, which
   promotes ullage de-encapsulation.

2. System weights for a manned Mars vehicle are given in Table 1 where the final
   comparison variable is converted to an initial mass in earth orbit (IMIEO).

3. In addition to ullage encapsulation of the mixer, ullage breakup by the mixer is
   important. Active mixing was observed to occur in regions distant from the
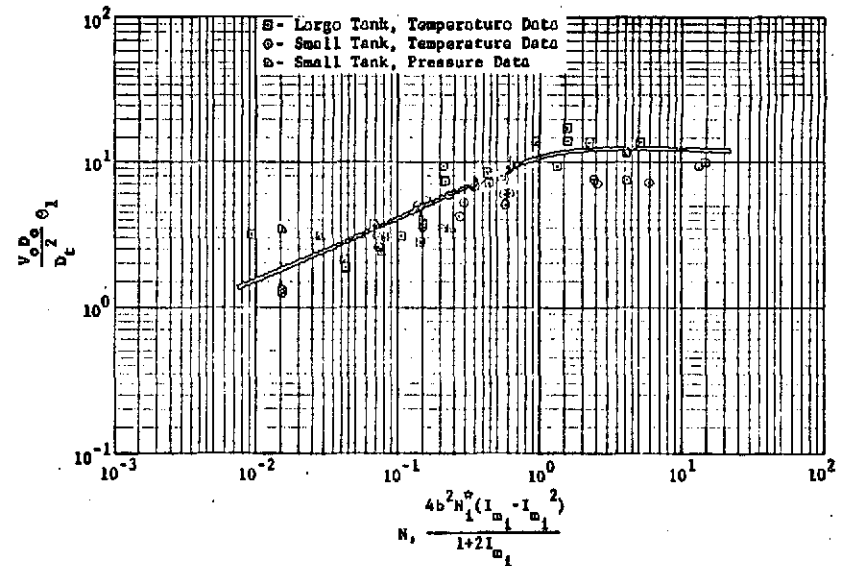   mixer. This led to design specification for mixers at both ends of the tank.
   However, the more stringent design performance criteria is ullage encapsulation.

4. Extensive design data are presented in the appendices for a range of mixer systems
   from small tanks to that for a manned Mars vehicle.

5. Additional work is required in pressure-temperature response mechanisms, boiling
   at heat shorts, ullage break-up, and buoyancy. Further development of brushless
   dc mixers is required. Experimentally, ullage encapsulation and ullage break-up
   must be examined in reduced gravity. Large tank tests are required to extend
   scaling,and orbital experiments should be defined to verify low-g mixing theory.

Table 1
MAXIXUM WEIGHT SUMMARY
(EXCLUDING STRUCTURAL SUPPORTS, ETC)
FOR BRUSHLESS D.C. MOTOR DRIVEN PUMP
INCLUDING ULLAGE ENCAPSULATION CRITERION

	EARTH ESCAPE STAGE	MARS BRAKING STAGE		MARS ESCAPE STAGE		
	EARTH ORBIT	EARTH ORBIT	EARTH TO MARS	EARTH ORBIT	EARTH TO MARS	MARS ORBIT
Fuel Cell Weight, lbs.	5.8	3.81		1.73		1.09
Boiloff Weight, lbs.	59.5	34.4		6.7		14.2
Pump Weight, lbs.	3.4	3.4		3.4		
Weight Per Tank, lbs.	69	42			27	
Weight Per Stage, lbs.	276	84			27	
Δ Imieo Per Stage, lbs.	497	263			122	
Total Δ Imieo, lbs.			848			

Figure 1. Comparison of Simplified Stratification Models for Typical Nuclear Flight Module Conditions

T_s = L/V interface temperature
T_b = bulk temperature
r_t = tank radius
θ = time

V_o = jet velocity at pump exit
D_o = diameter at pump exit
D_t = tank diameter
Z_b = distance from pump to L/V interface
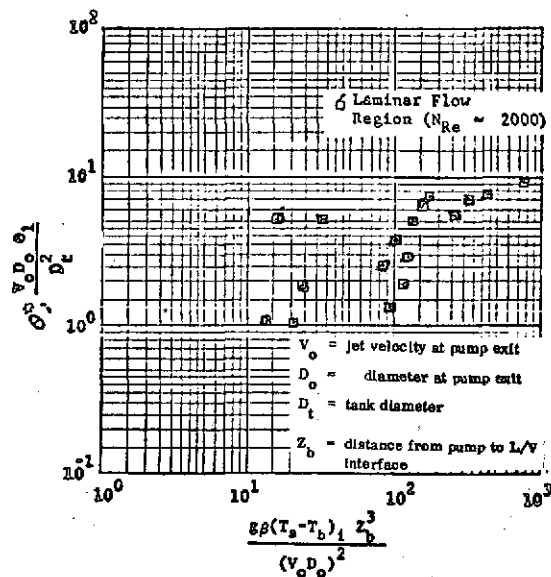
Figure 2. Correlation of Dimensionless Time For (T_s-T_b) to Reach 0.1 of its Initial Value: Open Tank Test
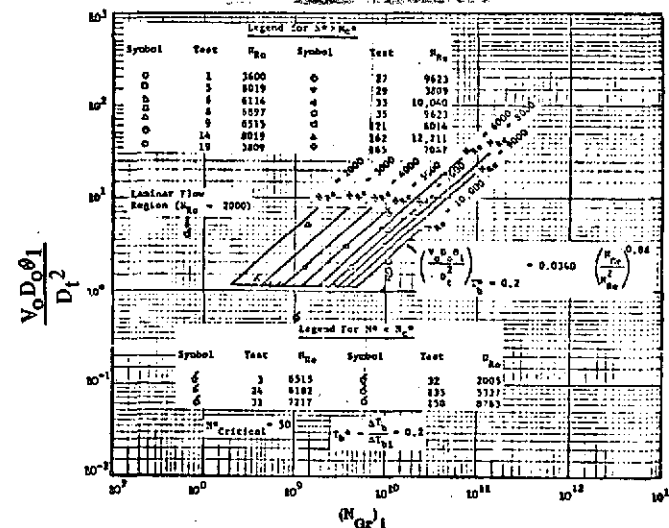
Figure 3. Correlation of Axial Jet Mixing Time Data for $(T_o-T_b)/(T_o-T_b)_i$ = 0.2: Open Tank Test

AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF GRAVITY
ON A FORCED CIRCULATION PATTERN IN SPHERICAL TANKS
Berenyi, S. G., et al, NASA-LeRC,TN D-4409, April 1968

OBJECTIVE. - To determine the minimum jet inlet velocity to maintain a stable flow
pattern as a function of tank size, acceleration level, and test fluid in spherical tanks
in reduced gravity.

PERTINENT WORK PERFORMED. - A series of fluid flow tests were performed in
the LeRC 2.2 sec drop tower with acceleration levels of 10^{-5}, 0.005, 0.01, 0.02,
and 1.0 g's to define thermal conditioning flow profiles. The flow patterns and con-
tainer sizes are shown in Figure 1; the test fluids were ethanol and water. Test cov-
erage was primarily photographic. In one-g tests, the velocity was increased until
the critical velocity was reached and the flow reached the tank top in a uniform, steady
manner. In low-g, this was achieved by bracketing the conditions on successive drops.
At velocities lower than critical, a center core did not form and fluid collected near
the tank inlet.

MAJOR RESULTS. -

1. The velocity required to maintain a flow circulation can be correlated in the form
   $V = C \, (R/\delta)^{1/2}$ where δ is the initial jet thickness and V is the mean jet inlet vel-
   ocity. The correlation for water is shown in Figure 2 where the tank radius non-
   dimensionalizes the abcissa and reduces the data to a single line. For ethanol,
   C = 37 and for water, C = 41.

2. The strong influence of gravity is shown in Figure 3. The range of low-g test data
   for ethanol are shown and the one-g correlation is given. A modified jet inlet
   velocity, $V/(R/\delta)^{1/2}$, can be used to normalize the data; the correlation with accel-
   eration level is shown in Figure 4. At lower than 4×10^{-3} g's, the critical jet
   velocity for complete circulation is independent of acceleration level. At higher
   accelerations, the critical velocity is proportional to $(ng/g)^{0.43}$ indicating a depar-
   ture from the expected Froude relation of slope 0.5.

COMMENTS. - The definition of critical velocities for inflow patterns has impact on
fluid-mixing design.
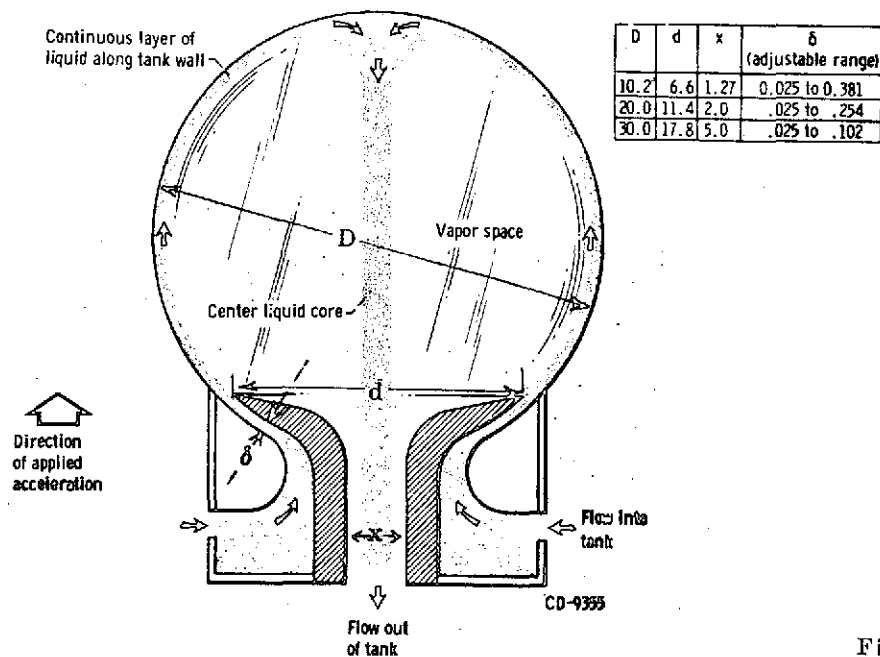
Figure 1. Desired Circulation Pattern

D	d	x	δ (adjustable range)
10.2	6.6	1.27	0.025 to 0.381
20.0	11.4	2.0	.025 to .254
30.0	17.8	5.0	.025 to .102

Figure 3. Velocity Required to Maintain Flow Circulation as Function of Wall Jet Ratio R/δ in Low-Gravity Environments With Ethanol
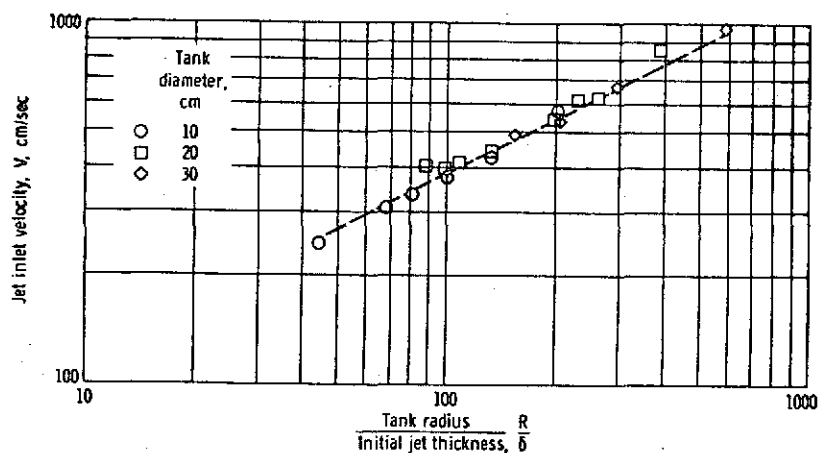
Figure 2. Velocity Required to Maintain Flow Circulation as Function of Wall Jet Ratio R/δ in Normal Gravity Environment With Water
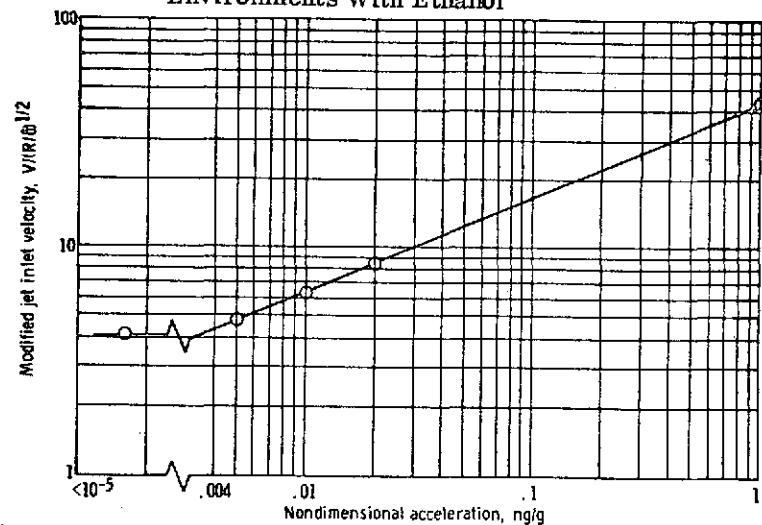
Figure 4. Effect of Gravity on Flow Circulation Requirements for 10-, 20-, and 30-Centimeter-Diameter Tanks. Test Fluid, Ethanol

ZERO GRAVITY PROTOTYPE VENT SYSTEM
Stark, J. A., Blatt, M. H., GD/C, NAS8-20146,
GDC-DDB67-006, October 1967

OBJECTIVE. - To define, design, fabricate and test a prototype heat exchanger
vent system capable of controlling tank pressure while discharging only GH_2, even
though the system and/or its inlet is in 100% LH_2 as may be encountered in space at
low-g.

PERTINENT WORK PERFORMED. - In the system definition phase, trade-offs were
made to determine the type of heat exchange (bulk vs wall), type of pump drive (electric
vs turbine), optimum vent flow rate, vent cycle, and fluid mixing criteria. Basic
design requirements were to control tank pressure to 17 ± 1 psia with external heating
of 20-30 Btu/hr over 14 days. The resulting system is shown schematically, as setup
for test, in Figure 1. Operation is by throttling the vent inlet to a low pressure and
temperature and flowing through the heat exchanger to vaporize any liquid which may
be present. Operation is intermittent to minimize total pump power input to the tank.
The pump provides forced convection exchanger flow as well as liquid temperature
destratification. Deactuation and actuation of vent and pump are controlled by a
pressure-switch. Testing was at 1-g with hydrogen in a 40-in. dia. by 84-in. long
superinsulated CRES tank. The system was located 22 in. from the tank bottom and
tests performed with the mixing flow (exchanger warm side outlet) directed (1) radially
(2) downward and (3) upward. In each case testing was performed with the unit in
vapor (13 in. LH_2 level) and liquid (49 in. and 70 in. levels). The 3-way valve (Fig. 1)
provided either liquid or vapor inlet at all tank liquid levels. Both steady state and
transient performance of the system was determined. In addition to the Figure 1
instrumentation, temperatures were measured throughout the tank fluid with platinum
resistance sensors.

MAJOR RESULTS. -

1. Feasibility and efficiency of the concept was demonstrated. No liquid was vented
   under all design operating conditions. A typical tank pressure trace is presented
   in Figure 2.

2. Tank fluid mixing and liquid/ullage coupling were found to be important for
   efficient pressure control. Operation with the system in liquid and the mixing
   flow directed down was inefficient and in fact, at a LH_2 level of 70-in., tank
   pressure was not controlled (Figure 3). Flow directed at the L/V interface was
   best for mixing with radial flow next.

3. An apparent freezing of LH_2 in the throttle valve during one of the tests was solved
   by locating the shutoff valve downstream of the heat exchanger and external to the
   tank.

Table 1. Pertinent Vent System Characteristics

Operation Cycle - Intermittent (on 1/30th of total)

Vent Flow - 3 lb/hr

Pump Power - 7 watts

Throttling Pressure - 5 psia

Test System Wt. - 11 lb. Est. Flight Wt. - 8.2 lb

Pressure Switch - 17 ± 1 psia with 0.5 psi min. deadband

Figure 1. Basic Vent System Test Schematic

3/8 in. line

Figure 2. Tank Pressure (Second Test Series, 9.6 to 11.0 Hours)

Figure 3. Tank Pressure (Third Test Series 21.5 to 22.5 Hours)

LEGEND

AL - System Actuates with Liquid Inlet

LG - Cycled Inlet from Liquid to Gas

GL - Cycled Inlet from Gas to Liquid

AG - System Actuates with Gas Inlet

9.0 REFRIGERATION AND RELIQUEFACTION

Covering systems to control tank pressure of space-stored fluids through refrigeration and/or reliquefaction.

ANALYSIS, DESIGN, AND DEVELOPMENT OF A PARTIAL
HYDROGEN RELIQUEFIER
Benning, M.A., et al, Air Products, Unnumbered Report,
NAS8-21203, October 1972

OBJECTIVE. - To design, fabricate, and test a partial hydrogen reliquefier charac-
teristic of flight type units.

PERTINENT WORK PERFORMED. - Various thermodynamic cycles which included
a compressor, an expander, various numbers of heat exchangers, and a para-ortho
hydrogen converter were analyzed. The converter was included to permit venting
equilibrium hydrogen, which is at a higher energy state than para hydrogen, to achieve
a greater heat sink per pound of vented fluid and thus increase the fraction of the feed
that can be reliquefied. A computer program was used to analyze the various cycle
configurations. It was concluded that the single most important factor affecting the
fraction of the feed reliquefied is the split of the feed between the compressor and
expander loops. The selected configuration and design point conditions for 29.4 psia
tank or feed pressure are shown in Figure 1. Characteristics for a 22 psia feed
pressure are presented in Figure 2.

Positive displacement machinery was used due to the low flow rates involved. The
expander and compressor pistons, mounted on a common crankshaft, have filled Teflon
rings and sealed bearings. The heat exchangers are the finned-tube type, and the
ortho-para catalyst is contained in segments between sections of one of the heat
exchangers (Figure 3). Four tests of the reliquefier were made at LH_2 temperature
with four different compressor piston ring designs. In none of the tests was a good
seal achieved, and it was concluded that a rather extensive design modification would
be required to solve this problem.

MAJOR RESULTS. -

1. A hydrogen reliquefaction system was designed and fabricated to reliquefy approxi-
   mately 43 percent of the feed gas flow at rates of 1.72 to 1.37 lbs/hr, depending
   on the feed pressure.

2. Attempts to provide an adequate seal for the compressor piston were unsuccessful.

COMMENTS. - The overall system weight is not given in the report. Data from Sexton,
et al, 1971, listed under "Fluid Management Systems (General)" in Appendix B indicates
the weight for this system is 200 lbs and requires 300 watts of power.
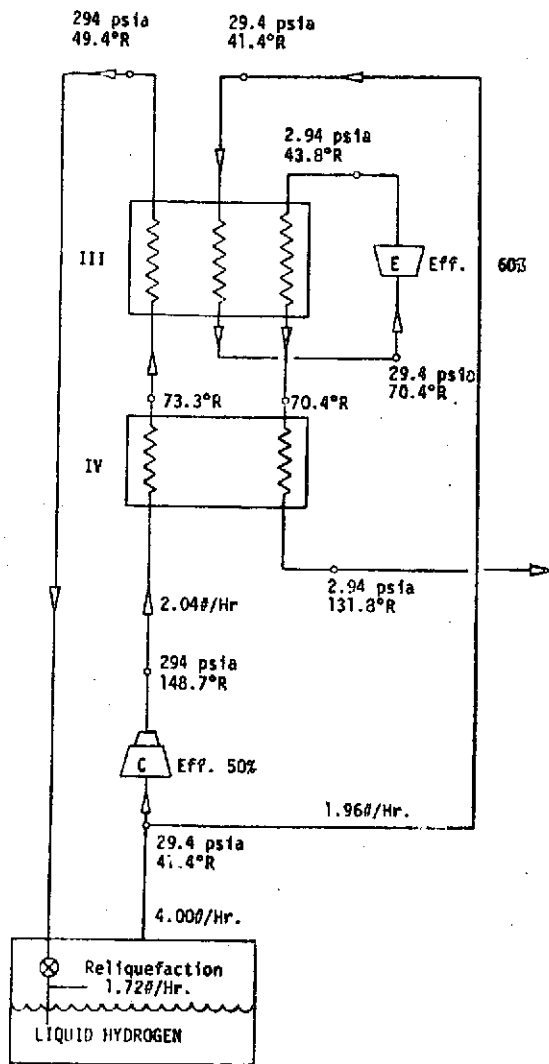
Figure 1. Design Point Conditions
(29.4 Psia Feed Pressure)
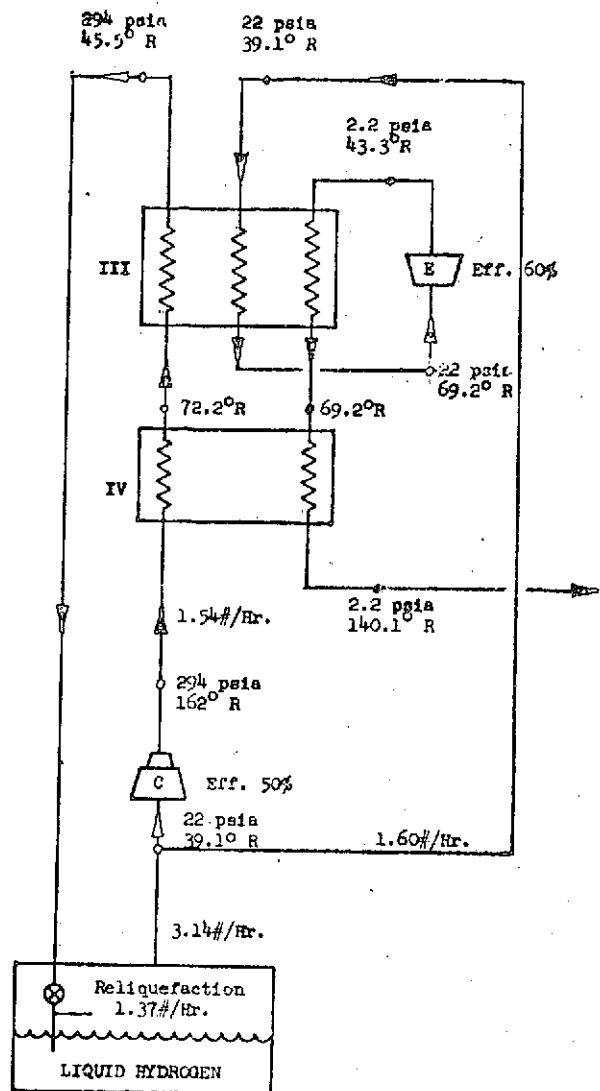
Figure 2. Design Point Conditions
(22 psia Feed Pressure)
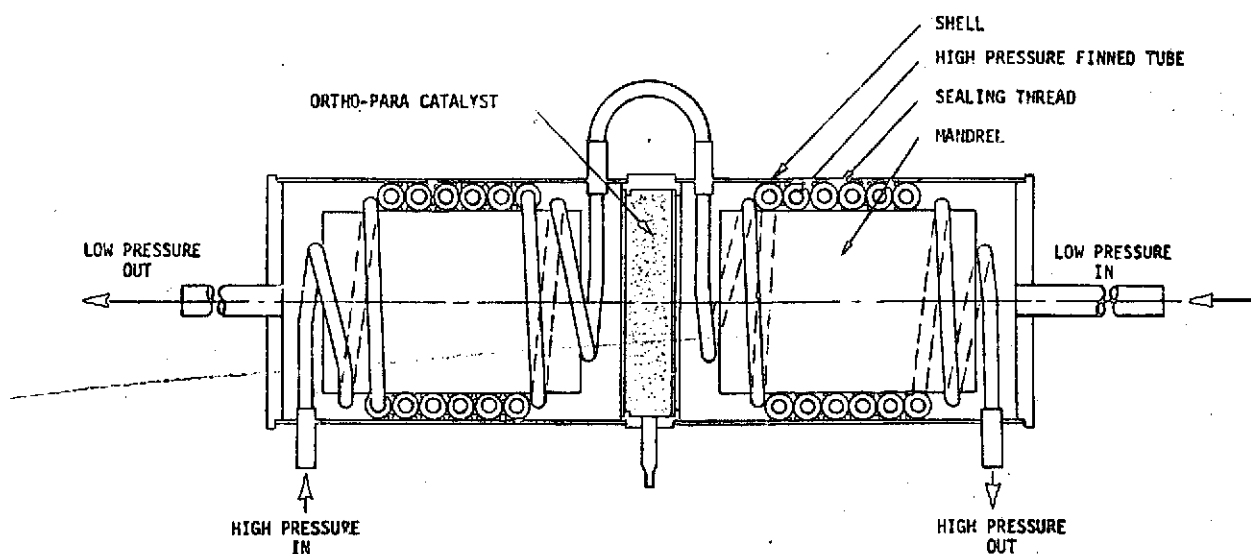
Figure 3. Test Heat Exchanger IV with Para-Ortho
Hydrogen Conversion Catalyst

INVESTIGATION OF EXTERNAL REFRIGERATION SYSTEMS
FOR LONG TERM CRYOGENIC STORAGE
Jensen, H.L., et al, LMSC, NASA CR-114920,
NAS9-10412, February 1971

OBJECTIVE. - To gather data on and investigate external refrigeration systems for
cooling cryogenic storage systems in long term space applications.

PERTINENT WORK PERFORMED. - Data were developed with the intent of providing
the designer with sufficient basic information to conduct rapid and accurate cryogenic
refrigeration system studies. Reports, data sources, and development programs on
small cryogenic refrigerators were reviewed. For long term (more than six months)
application it was found that non-vented systems show an advantage over vented
systems having no self-contained external refrigeration. Since cryogenic refrigerators
operate at relatively low efficiencies, the power supply and heat rejection devices be-
come important. A general lack of data on failure characteristics was found which
would be applicable to cryogenic and space applications.

The study presents basic information to obtain external autonomous refrigerator
performance, weight, and size (Figure 1). Means of estimating performance-reliability
tradeoffs are presented, as well as methods for computing tank surface temperatures
and radiator heat rates. Data are presented on weights of cryogenic tanks and vacuum
shells so that the designer can obtain trends and weight increments in conducting trade-
off studies. Weight estimating relationships for heat exchangers, helium circulation
compressors, cryogenic heat pipes, and power sources are presented. A large range
of the pertient parameters was given to make the data useful for a large variety
of space-oriented studies.

A handbook was prepared (LMSC-A984158) which is an extraction from the final report.
It is intended to provide the designer with a concise statement of the information and
procedures necessary to conduct system trade-off studies.

MAJOR RESULTS. -

1. A handbook of design information and procedures for conducting tradeoff studies on
   refrigeration systems was developed.
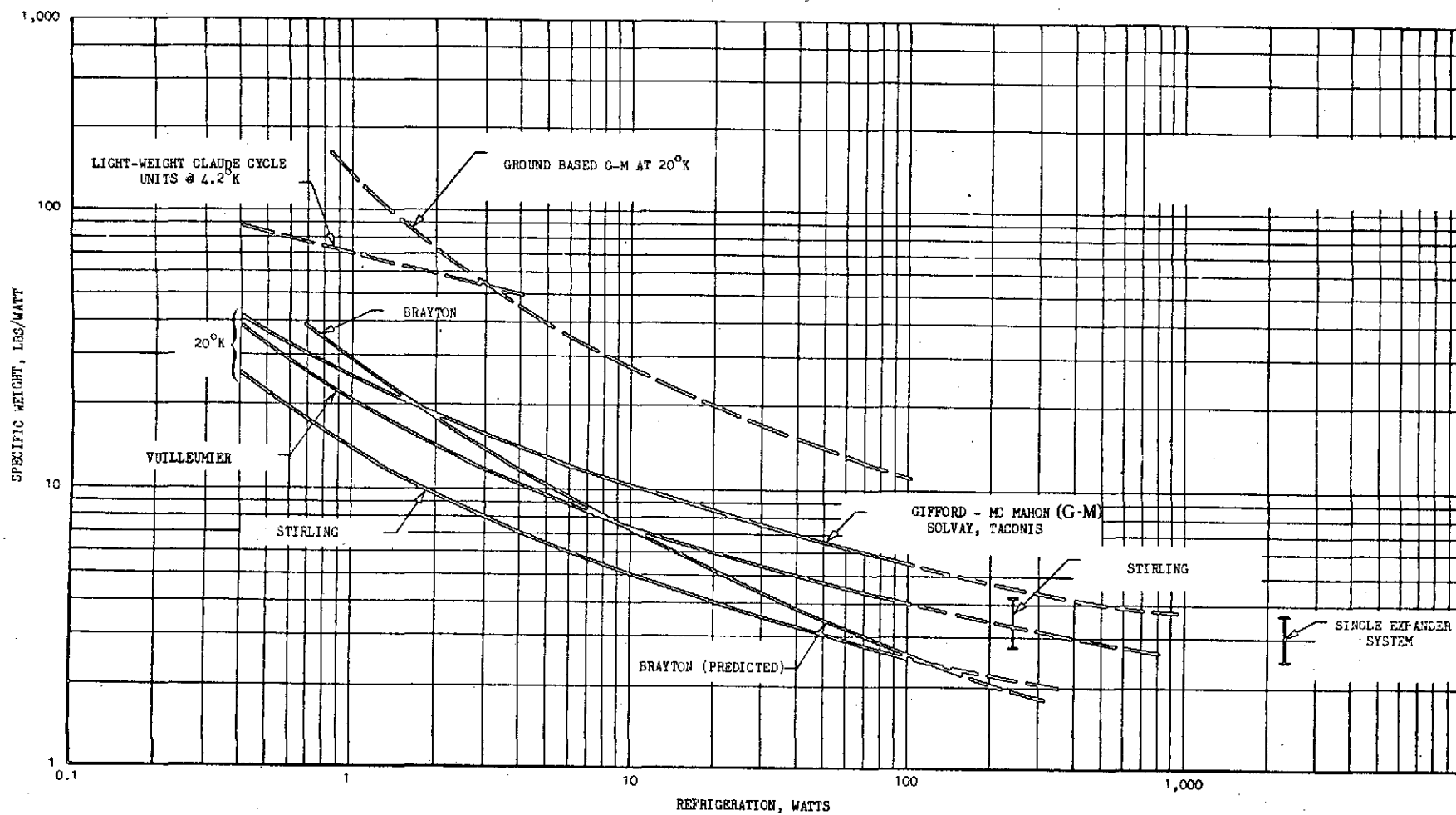
Figure 1. Summary of Refrigerator Weights vs Refrigeration
for Various Cycles at 20°K and 4.2°K

INVESTIGATION OF GAS LIQUEFIERS FOR SPACE OPERATION
Daunt, J.G., et al, Malaker Labs, ASD-TDR-63-775,
AF33(657)-10133, August 1963.

OBJECTIVE. - To determine the thermodynamic cycles best suited for use in space
for the liquefaction and reliquefaction of helium, hydrogen, nitrogen, fluorine, and
oxygen at rates from 1 to 1000 lbs per day.

PERTINENT WORK PERFORMED. - A survey is presented of the mode of operation,
performance, and efficiency of the following cycles: cascaded compressed vapor cycles,
systems using Joule-Thompson (J-T) cooling only, systems using expansion engines,
Stirling cycle systems, Taconis cycle systems, and miscellaneous other systems.
Data on the subject gases are presented followed by a theoretical survey of the relative
efficiencies of liquefaction and reliquefaction for ideal reversible cycles. Charts and
graphs presenting significant data on actual thermodynamic cycles used for refrig-
eration and reliquefaction are included which are based on conservative estimates of
the current state of the art and optimistic estimates of the probable future state for
the period 1965-70. Weights and volumes of existing compressors, motors, and
expanders are presented. Detailed qualitative (Table 1) and quantitative (Table 2)
comparisons of all the promising cycles are made on the basis of performance, weight,
volume, reliability, and compatibility with the space environment. Definitive conclu-
sions are arrived at which serve to permit specific recommendations for future action.

MAJOR RESULTS. -

1. A useful comparison of thermodynamic cycles for space liquefaction and relique-
   faction of cryogenic fluids has been assembled.

2. Based on the data given, the Stirling cycle systems were recommended for relique-
   faction and/or liquefaction of N_2, O_2, and F_2 for all production rates.

Table 1. Qualitative Cycle Comparison

	Systems Employing One Expansion Engine Only	Systems Employing Multi-Stage Expansion Engines Only	Systems Employing Expansion Engines Plus J-T Expansion	Stirling Cycle	Taconis Cycle
Main Causes of Inherent Irreversibility	Heat transfer at unequal heat capacity. Transfer of latent for sensible heat (reliquefaction).	Transfer of latent for sensible heat (reliquefaction).	J-T Expansion.	None	None
Listing of Heavy Components (Excl. Compressor, Space Radiator, Load Cooler)	Expander, Heat Exchangers.	Expanders, Heat Exchangers.	Expander(s), Heat Exchangers.	Regenerator. Expansion Piston.	Regenerator. Expansion Piston.
Location of Moving Parts (Excl. Compressor)	Expander.	Expanders.	Expander(s).	Expansion Piston.	Expansion Piston. Switch Valves.
Major Disadvantages in Space Environment	None	Large number of components.	Two phases in working fluid. Large number of components.	None	None

Table 2. Reliquefaction of H_2 at 1000 (100) lbs/day

System		Single J-T with Liquid N_2 Precooling at 65°K		Systems with One Expander.		Compound Systems with H_2 J-T.	Stirling Cycle with H_2 J-T.	
Coeff. of performance	Cons.	0.012	(0.012)	0.015	(0.015)	0.019	-	- (0.012)
	Opt. (Est)	0.015	(0.015)	0.019	(0.019)	0.022	-	- (0.015)
Required input power. kW for 1000 lb/day. (100)	Cons.	197	(19.7)	158	(15.8)	125	-	- (19.7)
	Opt. (Est)	158	(15.8)	125	(12.5)	108	-	- (15.8)
Compressor and motor weight. lb.	Cons. (up)	8000	(2600)	7300	(1900)	6400	-	- (1700)
	Cons. (low)	6900	(1050)	6300	(850)	5500	-	- (750)
Compressor, motor and liquefier weight lbs.	Cons. (up)	10300	2950	9700	(2500)	8500	-	- (2270)
	Cons. (low)	9200	(1400)	8400	(1130)	7300	-	- (1000)
		6100	(930)	5600	(760)	4900	-	- (870)
Radiator weight. lbs.	Cons.	15500	(980)	12000	(710)	9200	-	- (980)
	Opt.	12000	(710)	9200	(530)	7700	-	- (710)
Total weight of compressor, motor liquefier and radiator lbs.	Cons. (up)	26200	(4480)	21700	(3210)	17700	-	- (3250)
	Cons. (low)	21200	(2110)	17600	(1660)	15000	-	- (1710)
	Opt. (Est)	18100	(1640)	14800	(1290)	13600	-	- (1380)
Power generation subsystem weight. lbs.	Cons.	5700	(1300)	4950	(1200)	4200	-	- (1300)
	Opt.	3000	(800)	2500	(650)	2350	-	- (800)
Radiator area. sq. ft.	Cons.	4450	(445)	3550	(355)	2800	-	- (445)
	Opt.	3550	(355)	2800	(280)	2450	-	- (355)
Compressor Volume. cu. ft.	Cons. (up)	1000	(70)	850	50	650	-	- (23)
	Cons. (low)	750	(30)	550	20	450	-	- (14)
Compressor and liquefier volume. cu. ft.	Cons. (up) Cons. (low) Opt. (Est)	NO DATA AVAILABLE						

10.0 INTERFACE CONTROL AND LIQUID ACQUISITION SYSTEMS (GENERAL)

Covering systems and studies which consider various aspects of more than one of the following categories.

ZERO GRAVITY LIQUID TRANSFER SCREEN

Howard, F.S., NASA, U.S. Patent 3,744,738, July 1973

OBJECTIVE. - Describe a liquid transfer device for transferring liquid from one container to another in zero gravity.

PERTINENT WORK PERFORMED. - The liquid transfer device operates as follows: A spiral shaped screen (Figure 1) is rotated so that the surface tension created between the liquid in the container and the spiral shaped screen member directs the liquid out an exit port. The perforated screen is utilized so that back pressure created by the spiral shaped member can be relieved by allowing the contained liquid to pass through the spiral shaped member minimizing the back pressure. The transfer device adds very little heat to the liquid being transferred and minimizes the amount of venting required during transfer. The rotating shaft is turned by an electric motor. The periphery of the screen spirals are reinforced with a metal band.

COMMENTS. - This device combines the two concepts selected for propellant transfer in Stark, 1972. This concept should have high efficiency and low weight.
The back pressure control attributes of the spiral screen could be useful in a case where fairly low transfer rates are required.

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STUDY OF LOW GRAVITY PROPELLANT
TRANSFER-FINAL REPORT, Stark, J. A.,
GD/C, GDC-DDB72-002, NAS8-26236, June 1972

OBJECTIVE. - To perform an analytical assessment of potential methods for replenishing the auxiliary propulsion H_2, O_2 and N_2 cryogens which may be aboard an orbiting space station.

PERTINENT WORK PERFORMED. - This study included storage of supply fluid, transfer, and receiver tank pressure and temperature control. Systems considered were high pressure (supercritical), subcritical, and modular (transfer of the tanks). The baseline resupply requirement was 1,096 lb of H_2, 2480 lb of O_2 and 3,150 lb of N_2 to eight H_2, two O_2 and two N_2 bottles. The standard receiver tank was a 42.5 ft^3 sphere containing liquid at 100 psia for station use. In addition to the baseline conditions, weight and performance data were generated for bottle diameters from 25 to 150-in. and transfer fluid quantities from 500 to 5,000 lb of H_2 and 1,000 to 10,000 lb each of O_2 and N_2. Transfer line lengths were 20 to 200 ft. and the maximum disturbing acceleration was 10^{-4}g's. Both individual supply tanks for each receiver and a single supply for each fluid were considered.

Capillary screen, dielectrophoresis, bladders, bellows, diaphragms, and fluid vortexing methods of subcritical transfer were initially considered. On the basis of safety, weight and development potential only screen, metallic bellows, metallic diaphragm and paddle vortex sub-critical systems were selected for detailed analysis. The dielectrophoretic system was not chosen primarily on the basis of potential safety, since in O_2 there is still some question of electrical breakdown and combustion hazard associated with this high voltage system. Line and tank chilldown data are also presented and the feasibility of non-vent transfer was investigated for various operating conditions.

MAJOR RESULTS. -

1. Analysis of various high pressure supply heating and blowdown and receiver cooling schemes showed the only concept worthy of any consideration was one employing simple supply heating with increased receiver volume to allow for the reduction in transferred fluid density. Also, the final receiver fluid cannot be liquid since any requirement for condensation results in excessively high weight and power.

2. The surface tension and paddle systems were determined, on the basis of low weight and cost and high reliability and reusability, to have the best potential for the space station application. Typical system weight data are presented in Figure 1. Receiver tank weights are divided by 20 to reflect the fact that the receiver tanks stay fixed on the station for 20 supply cycles. Individual receiver weights are presented in Figure 2. The paddle vortex concept is illustrated in Figure 3.

COMMENTS. - The bellows work is reviewed under a separate summary.

Figure 1. Total H_2 Transfer System Weight (Supply + Receiver/20)

Figure 2. Receiver Weights for H_2 Transfer
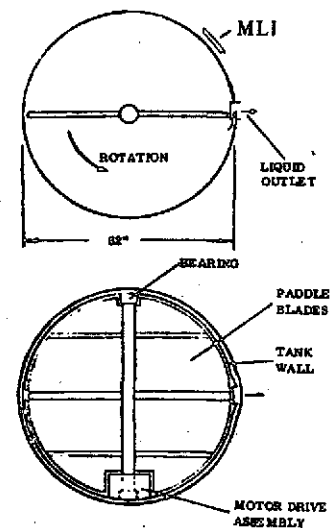
Figure 3. Paddle Type Vortex System

10-5

SATURN S-II ADVANCED TECHNOLOGY STUDIES, STUDY 8,
CRYOGENIC ACQUISITION AND TRANSFER, Schwartz, R.,
NAR, SD71-268, NASA Contract NAS7-200,
21 December 1971

OBJECTIVE. - Determine promising concepts of total capillary acquisition for LO_2/ LH_2 space shuttle main propulsion, attitude control and auxiliary power requirements. Perform bench tests to determine critical characteristics of capillary barrier materials. Specify testing required to verify system performance.

PERTINENT WORK PERFORMED. - Several thermal control concepts were analytically evaluated. Use of mixing, vehicle rotation, tank wall heat exchangers and heat pipes were examined for controlling thermal stratification. Thermodynamic vent system cooling capacity to condense vapor trapped in a capillary device was considered. Concepts considered for cooling of LO_2 with LH_2 were regenerative cooling, catalytic conversion from para to orthohydrogen, double walled tankage, vapor cooled shields, pumping of LH_2 over the LO_2 tank, a surge tank of cooled oxygen for periods when the hydrogen tank is not venting and internal mixing. A major consideration was prevention of freezing of LO_2 with the LH_2 coolant.

Vapor bubble collapse and condensation rates were determined analytically. A thermal stratification, self pressurization model was developed considering a laminar boundary layer, wall conduction, stratified liquid and vapor and a mixing region between the stratified liquid and the bulk subcooled liquid. Collector tube flow losses were computed.

Tests were run to determine screen pressure drop, bubble point, wicking rate, dewicking rate and collector flow losses. Dewicking tests were designed to qualitatively assess the ability of a screen to remain wetted when the liquid level supporting the wicking fluid is lowered.

MAJOR RESULTS. -

1. An active thermal protection system combining a thermodynamic vent system and vapor cooled shields was selected.

2. Screen configurations consisting of screened compartments were designed for the LO_2 and LH_2 tanks. Collector tubes were used in the LH_2 tank to supply inlet flow for thermodynamic vent system cooling.

3. Dewicking height properties of a capillary barrier material can be more critical than the bubble pressure.

4. Removal of trapped vapor pockets within the liquid by pressurization in low gravity did not appear practical due to long collapse times for large bubbles.

5. Figure 5.3-1, in the report, discussed recommended ground based and orbital tests.

COMMENTS. - Dewicking test results intuitively should yield test results similar to bubble point tests. Observed differences may be due to poorly controlled test conditions.

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POSITIVE EXPULSION
Heller, W., Cadwallader, E.A., CPIA,
CPIA Publication 210, May 1971

OBJECTIVE. Summarize the state of the art and developmental history of positive expulsion devices.

PERTINENT WORK PERFORMED. - The presentation was divided into seven chapters; Bellows, Cryogenic Bladders, Elastomeric Bladders, Teflon Bladders, Metal Diaphragms, Pistons and Surface Tension devices. Each chapter deals with definition of the positive expulsion concept, design features, programs, development history, current state of the art, problem areas and recommendations for future development.

MAJOR RESULTS. -

1. Bladders had been used as an expulsion device on more space vehicle programs than any other device. Fourteen flight programs had used Teflon bladders and nine programs had used elastomeric bladders. About 6,000 Teflon bladders and about 500 rubber bladders had been supplied for flight vehicles.

2. Surface tension screens had been used on six flight programs with 500 flight tests up to 1971.

3. Metal bellows had been used on six flight programs with 400 flight tests up to 1971.

4. One piston tank and one metal diaphragm tank had completed flight tests. Pistons had been used in 60 Lance hot firing tests which included several flight tests. A metal diaphragm was flight tested on an Army Missile.

5. Controlled folding devices should be considered for long life applications since they minimize three corner folds that shorten bladder or diaphragm life.

6. All the expulsion devices discussed in the report have high expulsion efficiency (96 to 99%). The major differences between the device are the differential pressure required for expansion.

7. Expulsion device testing should simulate actual operating conditions as closely as possible in order to eliminate scaling errors that have occurred in past programs.

8. Additional testing to evaluate dissolved gas and bubble formation in propellant expulsion tanks was recommended.

COMMENTS. - All flight tests were conducted with storable propellants. The fluid transfer system designer should examine this report to see if existing devices can be useful in accomplishing fluid transfer.

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ADVANCED PROPELLANT MANAGEMENT SYSTEM
FOR SPACECRAFT PROPULSION SYSTEMS,
Barksdale, T. R., et al, MMC
MCR-69-87, NAS9-8939, February 1969

OBJECTIVE. - Survey and evaluate propellant management techniques for the Apollo
Spacecraft Propulsion System.

PERTINENT WORK PERFORMED. - Six categories of propellant management systems
were evaluated: non-metallic bladders and diaphragms, metallic diaphragms, capillary
devices, sliding seal pistons, metallic bellows and miscellaneous systems. Primary
system goals were passive operation, high volumetric expulsion efficiency, low weight
and pure liquid delivery to the tank outlet. Secondary system goals were; insensitivity
to; propellant slosh, acceleration direction, engine duty cycle and off loading require-
ments, multicycle capability, series tankage capability, and no hardware change from
the configuration described in Table 1 and Figure 1. Evaluation criteria were adapt-
ability, reliability, state of the art, weight, development time and cost, expulsion
efficiency, passive operation, slosh control, series tankage capability, pressurant gas
ingestion,and adaptability to low g mass gauging systems.

MAJOR RESULTS. -

1. The non-metallic bladder material for fuel and oxidizer was chosen to be Teflon
    laminate based on low weight and material compatibility. A collapsing, single
    cell bladder of 10 mils thickness was selected.

2. A 10 mil thick Teflon laminate was chosen for the reversing non-metallic diaphragm.

3. A sliding sleeve, ring reinforced metallic diaphragm using a vent port to facilitate
    filling on the ground was the most promising metallic bladder or diaphragm
    configuration.

4. A capillary acquisition device consisting of a double compartment start basket
    with a screen liner in the bottom compartment was selected.

5. A center guided piston, sealed along the center guide rod and tank wall, was
    chosen for the piston design.

6. A titanium bellows design with a redesigned titanium tank was chosen for the
    bellows design.

7. Electrical systems, chemical foam systems, acoustic force systems and separate
    restart tanks were briefly considered but rejected, generally due to low level of
    technology development.

8. Table 2 compares the systems evaluated. A capillary device was selected as the
    recommended technique (Figure 2). A non-metallic bladder was the second choice.
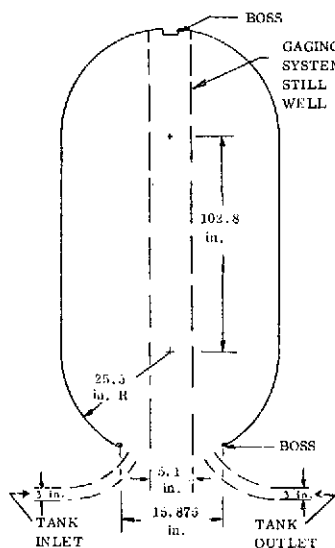
Figure 1. Oxidizer and Fuel Tanks
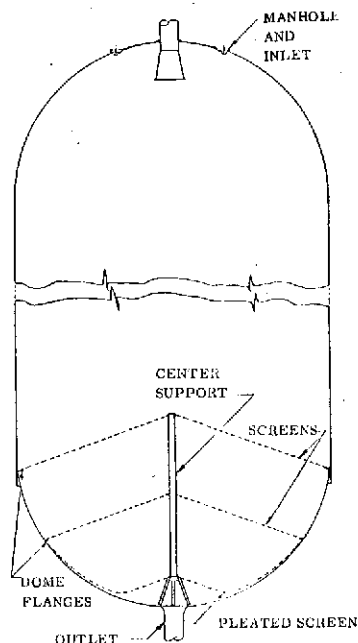
Figure 2. No Hardware Limitation Capillary Design

Oxidizer	Nitrogen Tetroxide, N_2O_4
Fuel	50% N_2H_4 – 50% $(CH_3)_2$ N_2H_2 **(by weight)**
Pressurant Gas:	Helium
Entering Temp.	$-50 \rightarrow +120°F$
Tank Volume	161.3 ft^3
Operating Pressure	175 to 220 psia (nominal)
Oxidizer Flowrate	39.26 lb_m/sec
Fuel Flowrate	24.54 lb_m/sec
Feedline Diameter	3.0 inch
Acceleration Levels:	
+g boost	$0 \rightarrow 7.35$
operation	$0.33 \rightarrow 0.94$
-g	$0 \rightarrow 0.2$
Transverse g	$0.009 \rightarrow 0.009$
Roll g	$-0.001 \rightarrow +0.001$ (5 deg/sec)
Restart Condition	$\leq 10^{-5}g$ 5 sec prior to restart
Pitch Rate	5 deg/sec
Vibration Levels	10 to 1000 cps at 3 db/octave increase, 1000 to 1500 cps at 0.3 g^2/cps spectral density. Decrease at 6 db/octave. Time: 700 sec in each of three axes.
Engine Duty Cycle:	
No. of Restarts	$0 \rightarrow 50$
Burn Duration	1 sec → propellant depletion

Table 1. Propulsion System Characteristics

Criteria \ Technique	Non-metallic		Metallic ①		Capillary Retention	Sliding Seal Pistons	Metallic Bellows
	Bladders	Diaphragms	Design A Cylindrical Rolling Diaphragm	Design B-2 Conospheroid Reversing Diaphragm			
Expulsion Efficiency, % (99.5% Goal)	98	99.5	99.5	99.5	99.5	99.5	97 - 99
Volumetric Efficiency within Tank Envelope, %	99.8	99.9	99	66	99.9	75	75
Weight lb (10-lb Goal)	32	38	104	32 ②	10.7 - 18.7	94 ②	91 ②
Pressurant Ingestion	Permeation of Pressurant	Permeation of Pressurant	None	None	Dissolved Pressurant	None with Good Seal Performance	None
Hardware Changes	Minimal Tank Redesign	Modest Tank Redesign	Modest Tank Redesign	Extensive Tank Redes.	Retrofit Possible	Extensive Tank Redes.	Extensive Tank Redes.
Duty Cycle Limitations	None	None	None	None	No. Restarts Constrained	None	None
Off-Load Propellant Limitations	Off-Load Not Desirable	Off-Load Not Desirable	Off-Load Not Desirable	Off-Load Not Desirable	None	None	None
Cycle Life	≈20	≈20	1 Reversal	≈6	>1000	1 Cycle	>1000
Propellant Exposure Tolerance, Yr (1-Yr Goal)	1	1	>1	>1	1	1	>1
Series Tankage Capability	No	No	No	No	Yes	No	No
State-of-the Art ③	1	1	5	4	1	3	2
Development Time and Cost ③	2	2	4	3	1	4	3

① All metallic systems are rated based upon titanium construction.
② Tank weight additions due to configuration change not included.
③ Relative Ratings - 1 through 5 where 1 represents best rating and 5 poorest. No absolute value significance is intended.

Table 2. Propellant Control Systems Evaluation Summary

STORABILITY DEMONSTRATION PROPELLANT
FEED SYSTEMS
Schuler, A.L., et al, GD/C, AFRPL-TR-67-252, AF04(611)-11545,
October 1967

OBJECTIVE. - To design, fabricate, test, and deliver to AFRPL twenty-three storable prepackaged propellant systems (SPPS) containing acquisition devices for a long-term storability demonstration.

PERTINENT WORK PERFORMED. - Each of the 15-gallon tanks contains either a Surface Force Orientation (SFO) device or a Rolling Diaphragm (RD) positive expulsion device. The 2219 aluminum tanks, 30 in. long and 13.75 in. in diameter, were subsequently loaded with MHF-5, N_2O_4, or ClF_5 prior to shipment.

The SFO device was required to be compatible with the propellants and pressurants for five years. It was not required to expel propellant in a negative gravity field, due to the unavailability of fine micron screen. The device consists of an aluminum alloy screen welded to a waffle-patterned backup plate. This assembly was circumferentially welded to the tank liquid outlet head prior to final tank assembly (Figure 1). MHF-5 was successfully expelled by the system during three demonstration tests.

The RD device had to meet the same requirements as the SFO device and be leak free. The RD shell and center tube are 0.032-in., 1100 aluminum alloy, bonded to the center guide and outer wall with silicone rubber adhesive (Figure 2). During testing, problems with shell collapse, piston cocking, and weld leakage were encountered and design changes made. The final four demonstration tests were successful.

One of the three pressurization subsystems was a liquid propellant gas generator consisting of a gas/hydrazine system separated by a bellows supplied by Metal Bellows Company.

MAJOR RESULTS. -

1. Twenty-three propellant storage systems were developed complete with acquisition and pressurization systems.

EXTERIOR VIEW

CUT-AWAY VIEW

BREAKDOWN VIEW
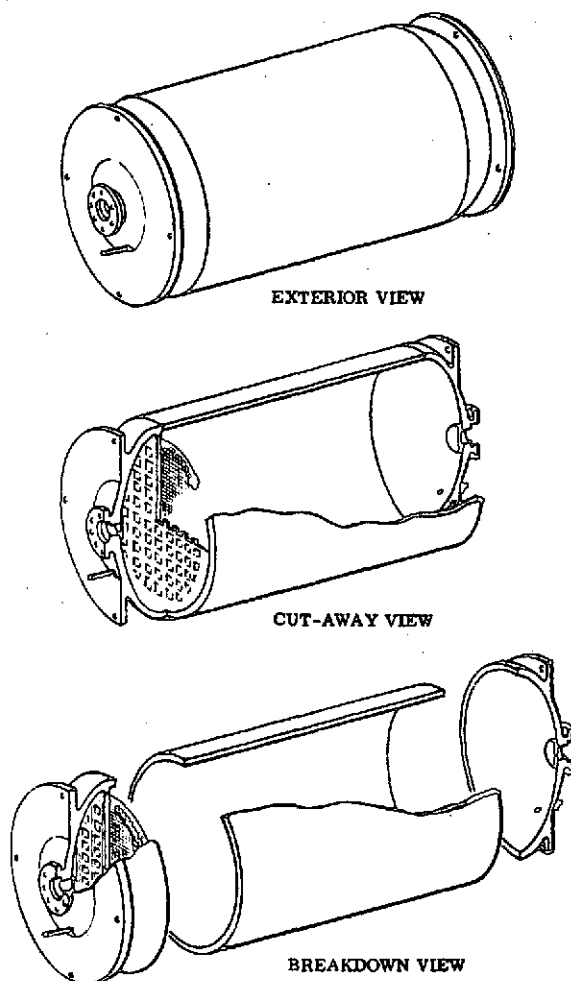
Figure 1. Propellant Tank With Surface Force Orientation Device

SILICONE RUBBER

GAS BULKHEAD

LIQUID BULKHEAD

SILICONE RUBBER

ROLLING DIAPHRAGM SHELL
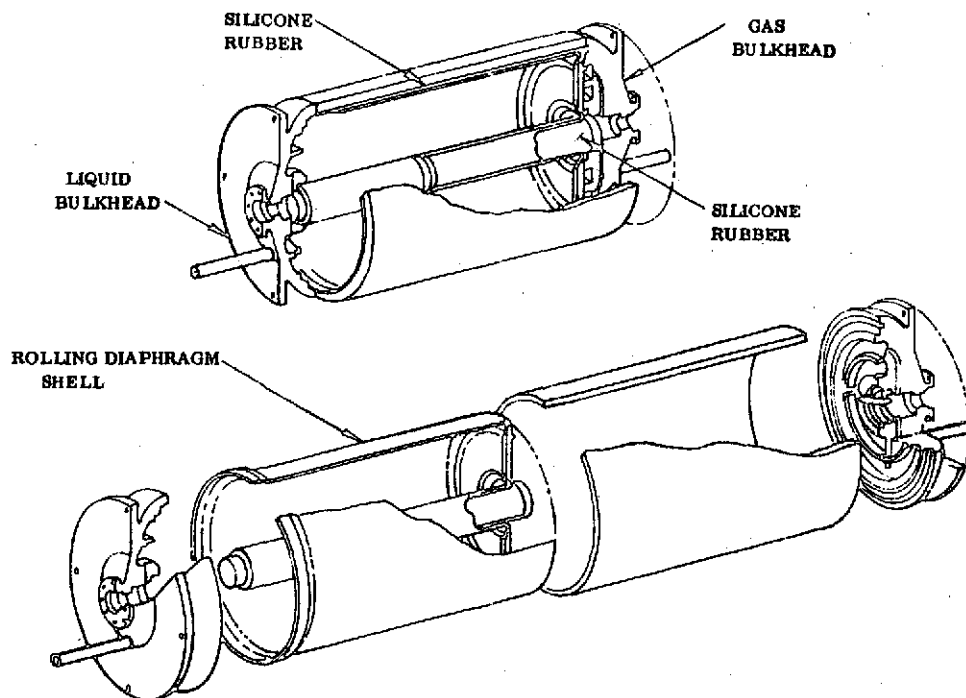
Figure 2. Propellant Tank With Rolling Diaphragm Device

IN-SPACE PROPELLANT ORIENTATION AND VENTING
EXPERIMENTS, PHASE I
Parmley, R.T., LMSC, AFRPL-TR-66-270,
AF04(611)-11403, October 1966

OBJECTIVE. - To design, fabricate, test, and deliver two identical surface tension
and two dielectrophoretic (DEP) propellant orientation units for orbital flight test.

PERTINENT WORK PERFORMED. - Phase I of this program included the experiment
definition, analysis, preliminary design, and the orbital test plans for both a surface
tension and a DEP propellant orientation device. The surface tension device used
allyl alcohol as a test fluid to simulate performance with N_2O_4, N_2H_4/UDMH, or
other storable propellants. The partial control concept, rather than total control, was
selected since it yields lighter system weights. The three-component device, shown
in Figure 1, consists of a truncated cone with holes located around the bottom for liquid
containment over the drain, a flat plate over the drain for reducing fluid velocities and
pull-through height, and a multi-baffled vent device. The spherical, Lexan test tank
is 12-in. in diameter. The liquid containment device is designed to be stable in all
directions for acceleration levels up to $10^{-3}g_o$.

The dielectrophoretic device was designed to demonstrate liquid orientation capability.
Liquid withdrawal, vapor venting, liquid collection times, anti-pullthrough charac-
teristics and the effect on slosh frequencies were to be determined. The DEP device
was installed in a 16-in. diameter Lexan sphere(Figure 2). The minimum electrode
spacing of 3 cm. and the spacing ratio of 2:1 were selected to provide the widest
range of test voltages and accelerations. Greater than $10^{-3}g_o$ adverse accelerations
can be tolerated with an electrode potential difference less than 100 kv. The electrode
assemblies and the high-voltage power supplies were fabricated by Dynatech Corp.
However, the DEP experiment was terminated early in the fabrication phase for
unspecified reasons.

MAJOR RESULTS. -

1. Two surface tension and two dielectrophoretic liquid orientation experiments
   were designed for orbital testing, complete with transparent tanks, lighting
   systems, and cameras.

2. In phase II of this program the two surface tension packages were delivered to
   AFRPL.

COMMENTS. - A surface-tension venting device similar to that used here was
subjected to aircraft zero-g tests. The results were reported by Bovenkerk, 1969,
summarized under vent systems.

VENT

VENT DEVICE

DRAIN

ORIENTATION CONE AND PULL-THROUGH SUPPRESSION PLATE
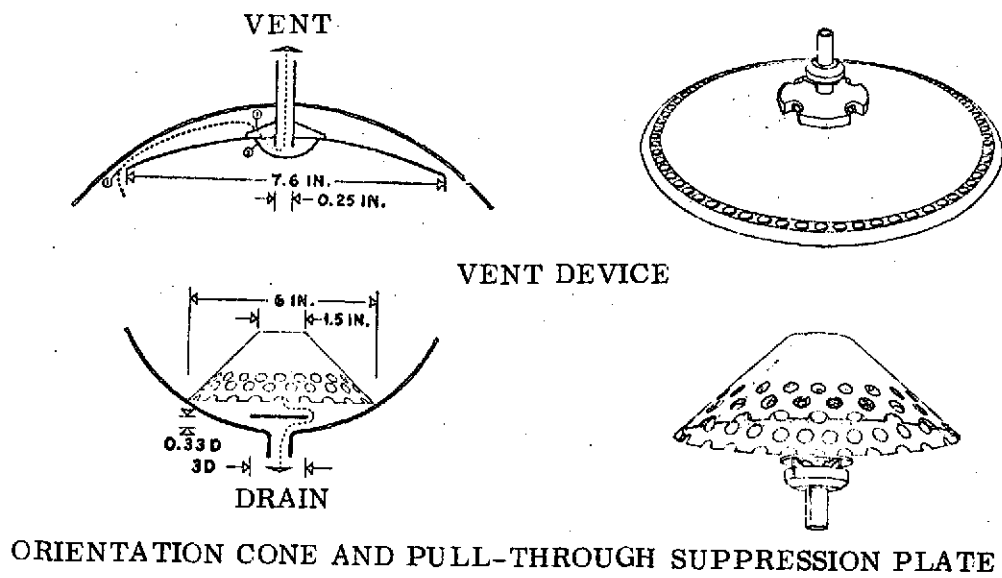
Figure 1. Surface Tension Orientation Device

$$\frac{S_{MAX}}{S_{MIN}} = 2$$

SPACE VENT

$S_{MAX} = 2.4$ IN. (6CM)

24 IN.

$S_{MIN} = 1.2$ IN. (3CM)

SPACE DRAIN

4.5°
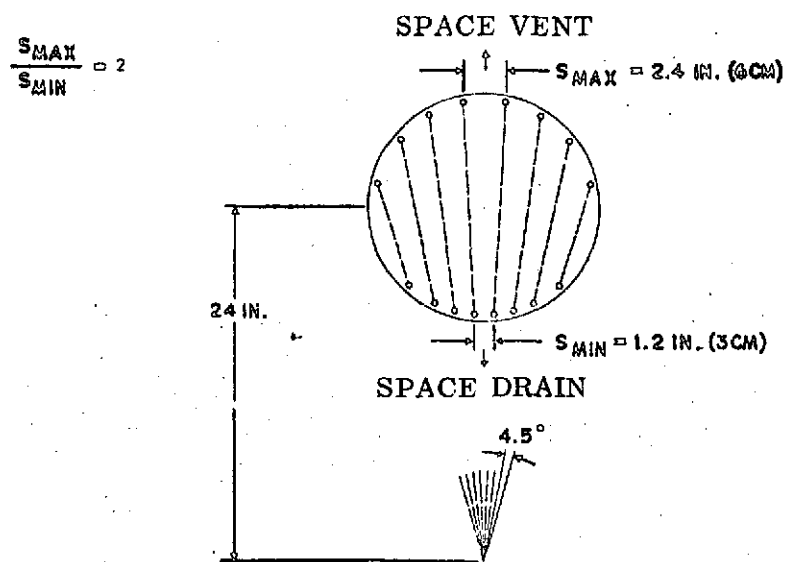
Figure 2. Selected Electrode Configuration

11.0 CAPILLARY ACQUISITION

Covering analysis, design, fabrication and test of systems using surface forces to control liquid orientation.

WICKING OF LIQUIDS IN SCREENS

Symons, E. P., NASA-LeRC, TN D-7657, May 1974

OBJECTIVE. - Analytically and experimentally determine the magnitude of wicking rates of liquids in screens.

PERTINENT WORK PERFORMED. - An analytical model was developed based on surface forces and Poiseuille flow that expressed the wicking velocity in terms of the geometry of the screen, and the surface tension and viscosity of the liquid. Data was obtained to evaluate the correlation constant C, representing all the screen geometric parameters, in the equation $V_w = (C/L) (\sigma/\mu)^{(1)}$, where L is the distance between the wicking liquid/vapor interface and the liquid source and V_w is the wicking velocity. Equations were generated for determining the local and uniform heat flux that could be intercepted by wicking flow in order to prevent drying out of a screen and loss of retention capability. $Q/W = (\delta\rho\lambda/2) (C/L) (\sigma/\mu)^{(2)}$ (local heat source) and $\dot{Q}/A_s = (\rho\lambda\delta/2) (C/L^2) (\sigma/\mu)^{(3)}$ (uniform heat source). See Table 1 for nomenclature.

Thirteen screen meshes were evaluated experimentally using methanol and ethanol as the test fluids. Tests were run in a horizontal wicking chamber on the ground and in a drop tower test package. Wicking displacement was measured visually as a function of time using a small scale having divisions of 0.1 cm. For the drop tower package, photographic data was used to measure displacement. Capillary pumping delivered liquid to the screen in the drop test package after the system entered zero gravity. Low wicking rates and short test times impaired the accuracy of many of the drop tower tests.

MAJOR RESULTS. -

1. Values of the correlation constant C were empirically determined and are shown in Table 2 for the ten dutch weave screens tested.

2. The square weave screens tested (150×150, 200×200 and 400×400) did not wick.

3. Predicted screen wicking capability (from equations 2 and 3) for preventing screen drying is shown in Figures 1 and 2 for local incident heat flux and uniform heat flux.

COMMENTS. - Results of Paynter, et al, 1973, indicate that order of magnitude increases in wicking can be obtained using screen/plate combinations compared to using screen alone.
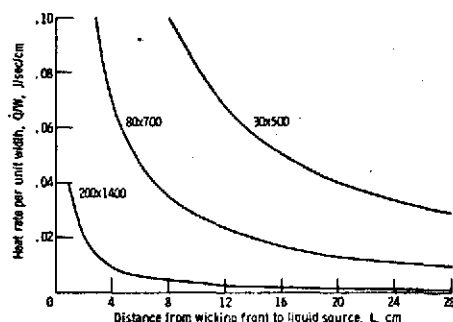
Figure 1. Maximum Local Incident Heat Flux as Function of Distance From Liquid Source. Wicking Flow Perpendicular to Warp Wires; Test Liquid, Hydrogen
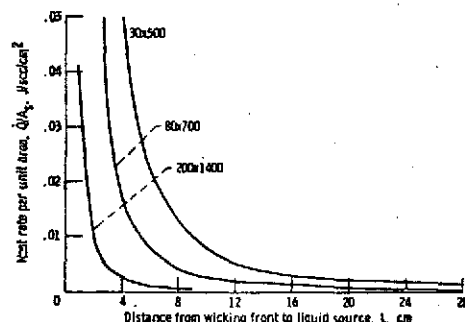
Figure 2. Maximum Uniform Heat Flux as Function of Distance From Liquid Source. Wicking Flow Perpendicular to Warp Wires; Test Liquid, Hydrogen

A_S area of screen surface, cm^2

C   correlation constant, μm

D_S manufacturer's rated pore size, μm

L   distance from wicking front to liquid source, cm

P   porosity of screen

$\dot{Q}$ applied heat rate, J/sec

V_w wicking velocity, cm/sec

W   screen width, cm

δ screen thickness, μm

λ latent heat of vaporization, J/g

μ liquid viscosity, g/cm/sec

ρ density of liquid, g/cm^3

σ surface tension, N/cm

Table 1. Nomenclature

Screen Mesh	Mfg's Rated Pore Size, D_S, μm	Screen Thickness δ, μm	Calculated Porosity, p	Direction of Wicking in Relation to Warp Wire	Correlation Constant c, μm
20x250 Twilled-weave dutch	30	685	0.399	Perpendicular Parallel	1.7 3.4
24x110 Plain-weave dutch	138	940	0.622[a]	Perpendicular Parallel	2.5 1.5
50x250 Plain-weave dutch	65	368	0.665[a]	Perpendicular Parallel	1.6 0.67
30x500 Twilled-weave dutch	57	430	0.428	Perpendicular Parallel	0.71 3.7
165x800 Twilled-weave dutch	37	147	0.533	Perpendicular Parallel	1.6 0.48
200x600 Twilled-weave dutch	30	135	0.614	Perpendicular Parallel	0.97 0.50
80x700 Twilled-weave dutch	40	254	0.368	Perpendicular Parallel	0.42 0.50
165x1400 Twilled-weave dutch	21	147	0.348	Perpendicular Parallel	0.19 0.38
200x1400 Twilled-weave dutch	14	135	0.272	Perpendicular Parallel	0.11 0.34
325x2300 Twilled-weave dutch	10	61	0.252	Perpendicular Parallel	0.11 0.17

[a]Measured

Table 2. Wicking Flow and Screen Geometry

DESIGN, FABRICATION, ASSEMBLY, AND TEST OF A LIQUID
HYDROGEN ACQUISITION SUBSYSTEM
Blackmon, J.B., Gaubatz, W.A., MACDAC, MDC G5360
NAS8-27571, May 1974

OBJECTIVE. - To analyze, design, fabricate and test a multipurpose full scale liquid
hydrogen acquisition and thermal control system (start tank) as part of the NASA/
MSFC auxiliary propulsion system breadboard.

PERTINENT WORK PERFORMED. - A screen device, consisting of a 24 inch diameter
24 inch long rolled spot welded 250 × 1270 stainless steel annular screen was designed
and fabricated to sustain an outflow rate of 7.5 lb/sec for 5 seconds against 1-g. The
device fit into a 6061 T6 aluminum cylindrical pressure vessel 34.5 inches high and
29 inches in diameter (Figure 1). The thermodynamic vent system (TVS) consisted of
flow control orifices (viscojets) and externally wall mounted dip brazed helical coils on
the cylindrical tank wall (0.25 in. D X 70 ft long in two 35 ft paths).

MAJOR RESULTS. -

1. The screen device performed successfully for both overhead and submerged
   diffusers using cold gas pressurization. Pressurization with warm hydrogen
   gas and, to a lesser extent, warm helium gas produced a marked decrease in
   retention capability.

2. Thermodynamic vent system flow control was achieved. Viscojet pressure loss
   predictions compared to actual viscojet and TVS pressure loss are shown in
   Figure 2.

3. Simulated low-g restart was achieved, involving IDU outflow followed by refill
   with simultaneous outflow.

4. Screen sealing with polyurethane adhesive and filling of gaps between the cooling
   tubes and the start tank wall with a conducting epoxy were successfully demon-
   strated with no adverse effect due to LH_2 immersion and repeated thermal cycles.

5. Two phase refill was demonstrated indicating that completion of settling is not
   required before start tank refill can be initiated.

6. A conical screen feedline barrier (shown in Figure 3) was successfully tested,
   using warm helium flow into the feedline at .004 lb/sec. This was equivalent
   to heating under the most severe conditions anticipated.

7. Malfunction of the submerged ball valves occurred repeatedly and seriously
   hampered testing.

COMMENTS. - A scarcity of quantitative comparisons of analytical predictions and
test data detract from this report. Empirical relations generally are not shown.
Perhaps this is due to test data being limited by ball valve actuation problems.

VENT TUBE

LEVEL SENSORS

31.5

COVER

SCREEN DEVICE

REFILL DIFFUSER

PRESSURANT DIFFUSER
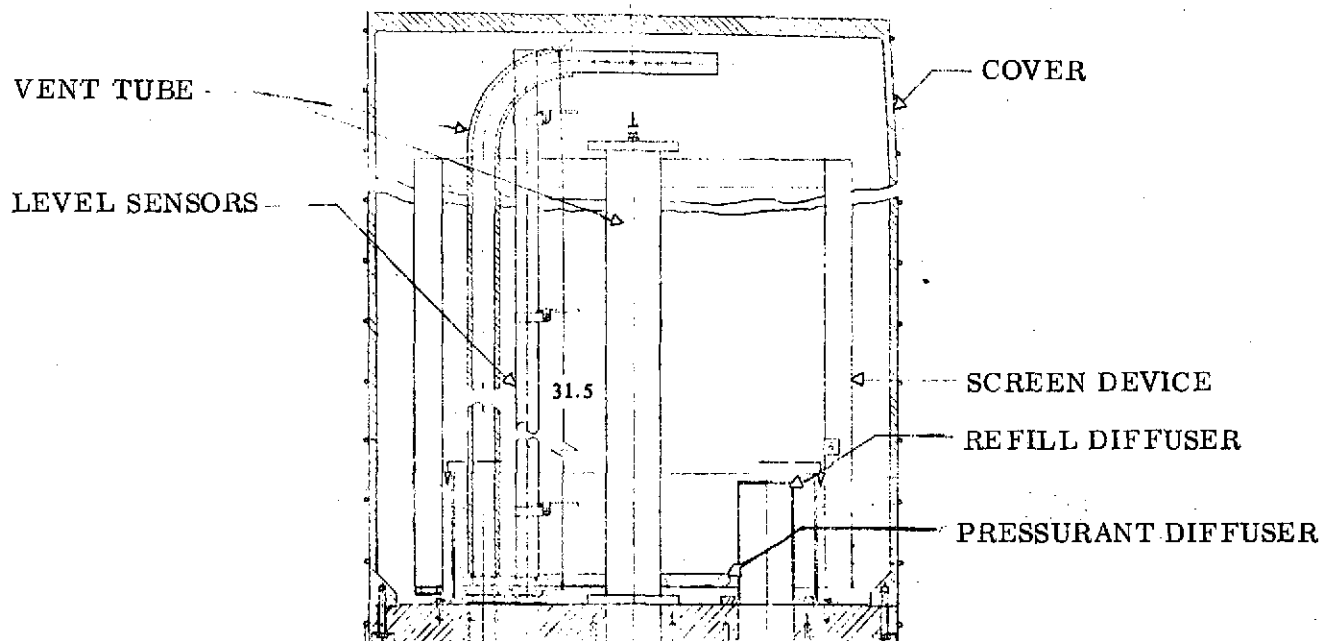
Figure 1. Conical Screen Feedline Barrier

DESIGNATION	PART NUMBER	LOHM READING
VJ1	38VL1-CM	32,600
VJ2	62VL4	17,600
VJ3	62VL1	8,900
VJ4	125VL2	5,650
VJ5	125VL1	4,000

NOTE: PRESSURE DROPS ACROSS VISCOJETS
ARE ACTUALLY LESS THAN MEASURED DROPS,
DUE TO PRESSURE DROP IN TVS (WHICH WOULD
BE GREATER FOR TEST D CONDITIONS)

COMBINATION VALVES
VJ2, VJ3
VJ2, VJ5, (VJ6)
VJ1, VJ3, VJ4, VJ5
VJ1, VJ2, VJ3, VJ4, VJ5
VJ1, VJ3, VJ4, VJ5
○ TEST H DATA
○ TEST D DATA

VJ1, VJ4
VJ5, VJ6

PRESSURE DROP THROUGH VISCOJETS (PSI)

MASS FLOWRATE (LB/HR)

Figure 2. Flowrate Dependence of Viscojets

3.0 in
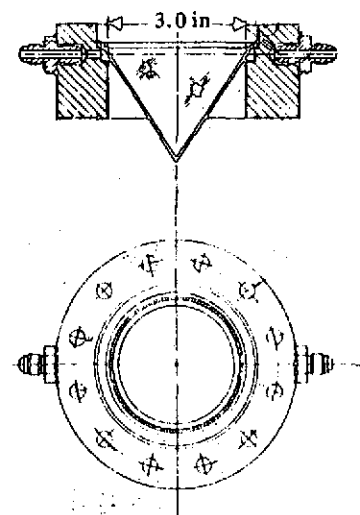
Figure 3. Vapor Barrier Screen

STUDY AND DESIGN OF CRYOGENIC PROPELLANT
ACQUISITION SYSTEMS, VOL. I - DESIGN STUDIES
Burge, G. W., and Blackmon, J. B., MACDAC, MDC G5038,
December 1973

OBJECTIVE. - Perform analytical and design studies to develop acquisition system
designs for an advanced Cryogenic Space Shuttle Auxiliary Propulsion System (CSS/
APS) and an Advanced Space Propulsion Module (ASPM) similar to a Space Tug.

PERTINENT WORK PERFORMED. Screen acquisition system sizing procedures were
developed and implemented in computing pressure differentials during system operation.
Fully distributed channel (FDC) and start tank concepts were designed for the Space
Shuttle and ASPM. The FDC concept, using cold pressurant, remains full of liquid until
the high acceleration reentry period. Pressurization tradeoffs and feed system transient
flow analyses were performed for the FDC. A localized pressure isolated channel (LPIC)
acquisition concept (start tank) was devised to minimize pressurization system weight by
permitting warm pressurant to be used in the main tank. Designs were presented incorp-
orating refilling with settled fluid and vacuum vent refilling (Figure 1) for refilling between
settling burns. Extensive calculations were performed to optimize insulation, venting,
pressurization and acquisition system requirements for both vehicles over a range of
possible missions. Both a screen ring and smaller screen device were fabricated for
integration into a NASA owned 105-inch tank. Settling analysis, based on empirical
correlations, predicted vehicle acceleration requirements for ASPM six-burn missions.

MAJOR RESULTS. -

1. Pump shutdown could cause backflow and ingestion of expanding, two phase fluid
    into the contained fluid. Pump bypass can be used to minimize backflow and
    pressure surge. Valve opening and closing effects were analytically found to cause
    pressure waves that could degrade screen performance (Figure 2).

2. Circular screened channels are recommended for good retention and low weight.

3. Thermal management studies indicate that vapor cooled shields are desirable (for
    vented tanks such as the ASPM LH_2 tank) to control incident heating into the tank
    contents. For unvented tanks (CSS/APS) internal mixers are recommended to
    control propellant stratification.

4. Acquisition concepts must be compared on an overall feed system basis. Figure 3
    illustrates the subsystem elements that should be included in the comparison.

5. For the six-burn missions analyzed, liquid settling has a lower weight penalty than
    the surface tension acquisition system.

COMMENTS. - The fully distributed channel and vacuum refill start tank concepts are
most applicable to low-g fluid transfer. Techniques used to optimize insulation thickness
and compare vented tanks to unvented tanks should be useful in designing supply tanks.
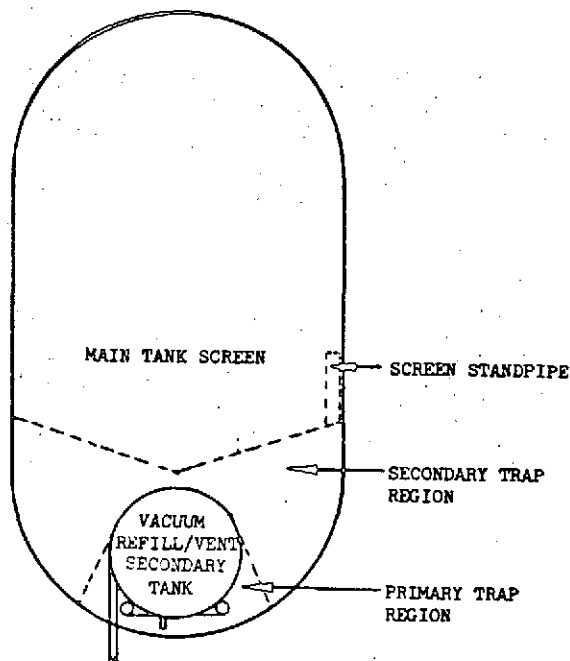
Figure 1. Main Tank Propellant Acquisition
for Start Tank Vacuum Refill
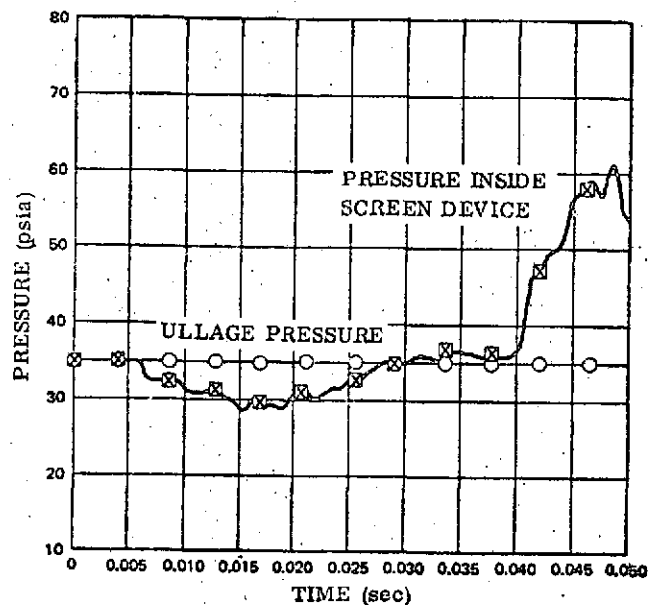
Figure 2. LH$_2$ Acquisition Subsystem
Shutdown Pressure History

	Distributed Channel Cooled Shield ? Cold Helium Pressurization	Pressure Isolated Channel Internal Mixer Thermal Control: 111° K GH$_2$ Pressurization
Weight	Higher weight	Minimum weight
Reliability	Fewer parts	Uses rotating machinery for propellant mixing
	Completely passive	Has potential retention breakdown correlation capability (+30 to 45 kg)
G-independent	All thermal aspects and critical flow characteristics can be tested on the ground	Internal mixer and refill involves some potential low-g uncertainties
Technology Status	In hand	Internal mixer involves some potential low-g uncertainties
Head potential for reqd screen mesh	About at limit of finest available mesh	Good safety factor with relatively coarse mesh
Fabrication capability	Must have access to all interior mesh	Tank within a tank fabrication
Pump bypass compatibility	Must dump all pump bypass	Could be handled with minimum or no dumping
Offloading	Severely limited capability	Complete flexibility

Figure 3. Overall Basic Concept Comparison

11-7

STUDY AND DESIGN OF CRYOGENIC PROPELLANT ACQUISITION
SYSTEMS, VOL. II, SUPPORTING EXPERIMENTAL PROGRAM,
Burge, G. W., Blackmon, J. B., MACDAC, MDC G5038,
NAS8-27685, December 1973

OBJECTIVE. - Develop experimental information to establish design criteria in the
areas of (1) basic screen characteristics; (2) screen acquisition device fabrication
problems, and (3) screen surface tension device operational failure modes.

PERTINENT WORK PERFORMED. - Evaluations were made of gas tungsten arc weld-
ing and roll spot welding of stainless steel plate and screen sandwiches, rivetted trap-
ezpoidal channel assemblies, screen element attachment by screws and nutplates and
repairing of screen characteristics and operational failure modes.

MAJOR RESULTS. -

1. Screen bubble point tests with LH_2 and GHe gave inconsistent results. Using GH_2
   pressurant, results were consistent and directly comparable to isopropyl alcohol
   results.

2. Flow losses using screen mesh and perforated plate were between 10 and 30% higher
   than losses with screen alone. Inserting a coarse mesh spacer screen between the
   plate and fine mesh screen reduced the pressure drop to that of the screen alone.

3. Degradation of bubble point due to pleating was found to be less than 20%, as shown
   in Figure 1. Considering total flow area of the screen, pressure losses were not
   measurably affected by pleating.

4. Deflection tests indicated no significant bubble point degradation and no load cycle
   dependence.

5. Warm gas can seriously reduce the retention capability of fine mesh screen, as
   shown in Figure 2.

6. Direct heat transfer to a screen supporting saturated LH_2 did not cause reduction
   in retention capability as anticipated.

7. Screen vibration (using screen samples having natural frequencies much greater than
   the maximum shaker frequency) had an unpredictable effect on retention capability
   (see Figure 3).

8. Multilayer screen barriers cause trapped gas to be forced downstream into the pro-
   pellant feed system. The bubble point of the multilayer unit must be exceeded to
   expel this gas, creating a possible gas ingestion problem in the capillary feed.

9. Large screen devices can be bubble point tested with a film condensation method.

10. Settling tests indicated that momentum refill should not be relied upon for capillary
    device refilling.
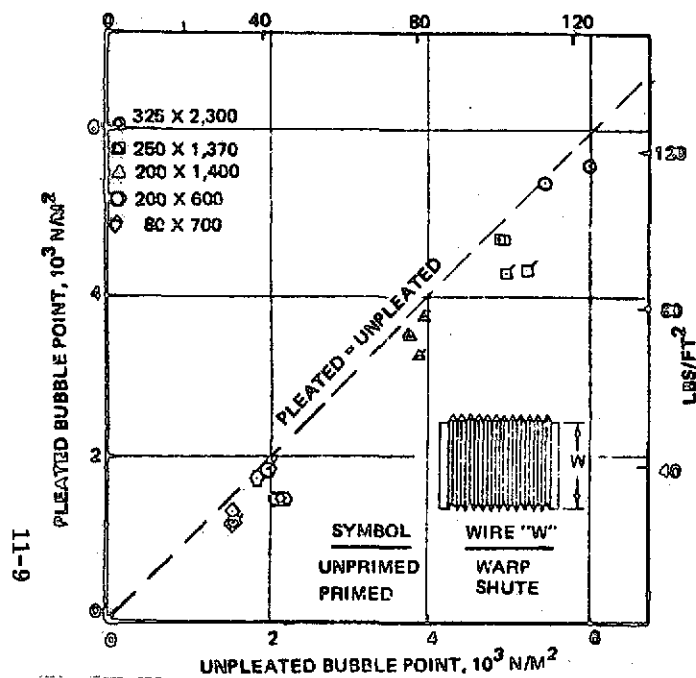
Figure 1. Bubble Point Performance of Pleated Screens

SYMBOL | WIRE "W"
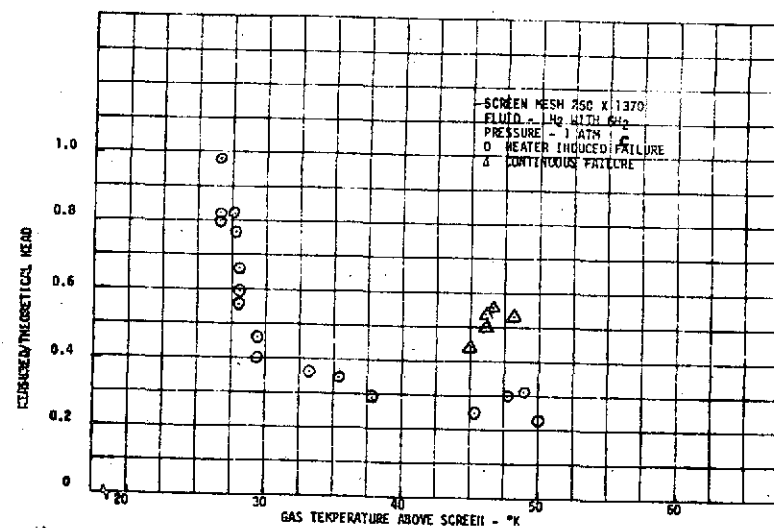
Figure 2.   Influence of Warm GH_2 Above Screen Retaining LH_2
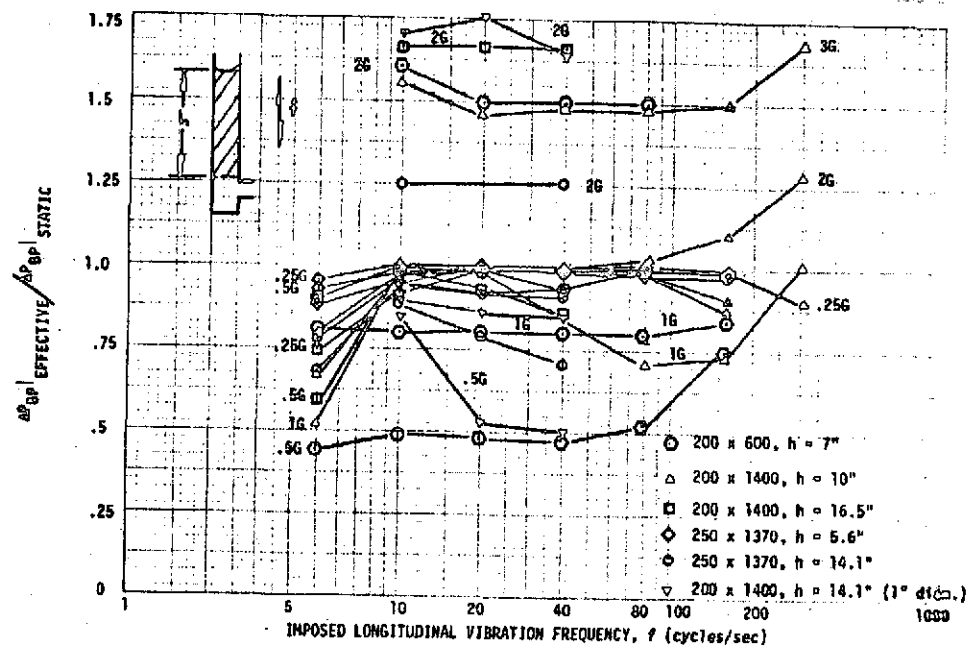
Figure 3. Longitudinal Vibration Effects on Bubble Point for Liquid Columns

SIMILARITY TESTING OF SPACECRAFT CAPILLARY PROPELLANT MANAGEMENT SYSTEMS
DeBrock, S.C., LMSC, AIAA Paper No. 73-1228, Nov. 1973

OBJECTIVE. - Demonstrate the use of similarity testing for verifying the performance of spacecraft capillary propellant management systems.

PERTINENT WORK PERFORMED. - Since capillary forces do not dominate most full scale propellant management systems in a 1-g laboratory environment, the model scale, acceleration environment, propellant flow rate and/or test fluid properties must be adjusted to maintain the same balance of forces found in the prototype. Dimensionless groups may be used to yield identical scaled performance from the model to the prototype.

The various test methods available for similarity testing are compared in Table 1. Descriptions of bench testing used for surface tension devices were given for evaluating; surface tension by the Sugden Method, transient acceleration loading (shock) effects on capillary device retention; transient propellant withdrawal, propellant reorientation and sump refill.

Drop tower tests were described for; determining initial low g propellant orientation, time required to deorient the propellant, and associated propellant motion.

MAJOR RESULTS. -

1. Similarity test methods have been proven to successfully predict prototype performance. In the Agena development program, expulsion efficiency tests with plastic sumps and water were compared to subsequent full scale propulsion subsystem hot firings. Other examples of similarity test comparison methods are given in Table 2.

2. Similarity test techniques have been used to accurately predict flight performance as shown in Table 3.

Table 1. Similarity Test Approach Comparison

Type	Approach	Application	Strengths	Limitations
1-g Bench	Use dimensionless groups to scale model size, test fluid properties and test conditions.	Evaluate propellant withdrawal, bulk static and dynamic behavior.	Convenience; controlled test conditions; rapid turnaround and low cost.	Model size becomes small at low prototype accelerations; does not duplicate low-g initial conditions.
Immiscible Test Fluids	Immiscible test fluids with similar densities reduce body forces.	Evaluate bulk propellant configurations.	Convenience; controlled test conditions; rapid turnaround and low cost.	Limited to static bulk evaluations.
Electromagnetic Field	Colloidal suspension of magnetic particles "supported" by electromagnetic field.	Evaluate propellant withdrawal, bulk static and dynamic behavior.	Variable body forces	Model size limited by size of magnet; does not provide low-g simulation of gas or vapor phase; impaired visibility.
Aircraft Testing	Keplerian trajectories used to produce weightlessness.	Evaluate propellant withdrawal, bulk static and dynamic behavior.	Produces true low-g environment for relatively long periods.	Poor control of g magnitude and initial conditions; relatively expensive and time consuming.
Drop Tower	"Free fall" of test platform.	Evaluate propellant withdrawal, bulk static and dynamic behavior.	Precise control of test conditions; reasonable test turnaround; variable body forces.	Relatively short test period; small models for modest facilities.
Orbital Test	Use orbital vehicle as test lab.	Evaluate propellant withdrawal, bulk static and dynamic behavior.	Long test periods in true low g environment.	Variable g required special test equipment or the total vehicle must experience test g's.

Table 2. Similarity Test Comparison

Vehicle Event	Capillary System Parameter Monitored	Similarity Test Method	Results	Observations
Low-g Coast	Propellant Bulk Configuration	Two liquid neutral buoyancy; low-g drop tower	(a) Low-g configuration has been correlated between two liquid neutral buoyancy vs. drop tower tests; (b) drop tower tests of a common design have shown the same results at 1/36 and 1/12 scale with different test fluids.	(a) > 7 (b) > 12
Low-g Engine Startup	Arresting or low-g surface dip	1-g Bench	1-g bench tests of similar designs have been conducted with water and kerosene at scales of 1/6, 1/5, and 1/4 and show identical results	> 100
Propellant Reorientation	Propellant reorientation mode and time	Low-g drop tower; 1-g bench	Low-g drop tower and 1-g bench tests have been conducted with water and kerosene at scales of 1/4, 1/3 and 1/1 and show similar results when normalized to the same scale, g and test fluid	> 40
Expulsion Efficiency	Arresting of high-g surface dip	Full scale 1-g bench, full scale test firing	Residual propellant from 1-g hot fire tests agreed with 1-g full scale water flow bench test results within ±10%	Bench ≈ 18 Hot firing ≈6

Table 3. Similarity Test Comparison With Flight Data

Vehicle Event	Capillary System Parameter Monitored	Similarity Test Method	Parameter Monitored	Flight Instrument	Flight Performance	Observations
Low-g Coast	Static Propellant Bulk Configuration	Two liquid neutral buoyancy; low-g drop tower; 1-g bench; magnetic fluid; aircraft	Vehicle lateral and axial acceleration	Accelerometer	(a) Small oscillations in lateral acceleration verify predicted symmetric propellant low-g bulk configuration; (b) Initial axial acceleration overshoot during low-g Agena restart verified predicted forward tank location of propellants	(a) ≈ 10 (b) ≈ 10
Vehicle Maneuver/ Disturbance	Bulk Propellant retention within capillary devices	Low-g drop; 1-g bench	Engine gas ingestion	Pump Inlet and thrust chamber pressure transducers	Gas-free engine restart after many days of vehicle maneuvers verified propellant retention capability	> 40
Low-g Engine start-up	Arresting of low-g surface dip	1-g bench	Engine gas ingestion	Pump Inlet and thrust chamber pressure transducers	Gas free engine restart after many hours of vehicle coast verifies low-g surface dip performance	> 70
Steady Engine Firing	Steady low-g gas arresting	1-g bench	Engine gas ingestion	Propellant feed system and thrust chamber pressure transducers	Gas-free low-g engine propellant feed substantiates predicted performance	> 100
Propellant Reorientation	Propellant destabilization time, reorientation mode and time	Low-g drop tower; 1-g bench	Vehicle Axial acceleration	Accelerometer	Vehicle axial accelerometer showed initial acceleration overshoot during propellant reorientation followed by acceleration undershoot as mass impacted tank bottom.	≈ 10
Refill of Capillary Devices	Separation of entrained pressurization gas and gas expulsion	Low-g drop tower; 1-g bench	Engine gas ingestion	Pump inlet and thrust chamber pressure transducer	Gas-free engine restart verifies sump refill during prior engine burn.	> 70
Expulsion Efficiency	Arresting of high-g surface dip	Full scale 1-g bench; full scale test firing	Propellant head and propellant tank pressure	Pump Inlet and propellant tank pressure transducers	(a) Rapid pump inlet pressure decay signaled depletion. (b) Time to vent residual propellant verified sump expulsion efficiency	> 12

ACQUISITION/EXPULSION SYSTEM FOR EARTH ORBITAL
PROPULSION SYSTEM STUDY, VOL. 5; EARTH STORABLE
DESIGN, Fester, D. A., MMC, MCR-73-97,
NASA-CR-134157, NAS9-12182, October 1973

OBJECTIVE - Define the design parameters for an earth orbital maneuvering system
(OMS) passive acquisition/expulsion device through analysis and testing.

PERTINENT WORK PERFORMED - Fuel and oxidizer trap (start basket) designs were
selected for satisfying mission requirements. Ground testing was conducted to provide
support information for the design activity. Lateral screen stability and bubble point
tests were conducted with multiple screen barriers. Centrifuge testing was used.
Testing was conducted with 180 x 180, 200 x 1400 and 325 x 2300 mesh screens. These
represent the finest meshes available in titanium, aluminum and stainless steel
respectively. Gas penetration data was obtained in centrifuge tests conducted at
accelerations above those required to exceed the retention capability of a single screen
layer. A quantitative model was developed for predicting multiple screen breakdown
under lateral acceleration. A small scale model complete screen liner and subscale
trap were fabricated and used to study ground handling requirements and procedures.
Acceptance tests, functional inspections, and propellant loading and draining procedures
were investigated in bench tests. Acceptance testing consisted of bubble point and drip
testing. Bubble point testing was conducted by submerging the screen liner in methanol
and pressurizing while rotating the liner. The same model was used to study shock and
vibration during ground handling. Screen liner flaws were repaired with eutectic solder.
Drip tests were conducted by filling the liner with liquid, lifting it out of the bath and
rotating the liner so that it supported increasing hydrostatic head. Liquid dripping
out of the liner denoted the retention limit of the 80 x 700, 250 x 1370 and 325 x 2300 mesh
screens tested. Remote bubble point tests were also run with a spray technique,
measuring the pressure differential across the wetted liner.

MAJOR RESULTS -

1. Recommended joining methods for surface tension devices are shown in Table 1.
   Resistance welding is the most desirable method. High temperatures caused by
   fusion welding can destroy the screen.

2. Possible failure modes of screen devices are shown in Table 2.

3. Data presented in Figure 1 illustrates the deviation from additive bubble point
   capability of multiple dutch twill screen layers.

4. A generalized relationship of the breakdown characteristics of multiple screen
   barriers under high lateral accelerations, indicated that multiple-screen barriers
   of fewer layers than required for lateral stability can be designed to provide barrier
   breakdown transients on the order of minutes rather than seconds.

5. Testing demonstrated loading and ground handling of liner and trap devices.

Table 1. Recommended Joining Methods for Surface Tension Devices

| | MATERIAL | | | | | |
| | Stainless Steel | | Aluminum | | Titanium | |
	Screen-to-Screen	Screen-to-Plate	Screen-to-Screen	Screen-to-Plate	Screen-to-Screen	Screen-to-Plate
Resistance Welding	x	x	x	x	x	x
Fusion Welding						
Electron Beam Welding	x	x			x	x
Brazing		x		x		
Soldering		x		x		
Mechanical Fastening		x		x		x

Table 2. Causes of Failure of Surface Tension Devices

Failure Mode

Gas Entering Engine

Insufficient Liquid in Reservoir (Applies to Trap Devices Only)
- Dryout of Coverplate
  - Loss of Wicking Capability - Clogged by Contamination or Corrosion, Fracture of Screen Wires
  - Unexpected Pressurant Impingement
- Loss of Liquid due to Thermal Effects
  - Excessive Thermal Cycling - Expansion and Contraction of Liquid
  - Excessive Vaporization
- No Supply of Bulk Liquid
  - Excessive Slosh in Settling
  - Low Engine Thrust
  - Clogging of Pores by Contamination or Corrosion
- Decrease in Retention Capability of Coverplate

Gas Entering Annulus
- Decrease in Retention Capability of Liner
  - Enlargement of Pores by Corrosion, Excessive Structural Loads
  - Excessive Accelerations
  - Structural Failure - Excessive Structural Loads, Fatigue due to Vibration, Slosh Loads
  - Change in Liquid Properties (Surface Tension, Density, Contact Angle) - Variation with Temperature, Contamination, Corrosion Products Exceeding Expected
- Excessive Pressure Losses within Annulus
  - Hydrostatic Head - Excessive Accelerations
  - Flow Area Change - Structural Failure Constricting Annulus
  - Flow through Screen - Clogging due to Contamination or Corrosion
  - Friction Losses - Structural Failure, Corrosion
- Boiling of Liquid in Annulus
  - Excessive Heat Soakback from Engine
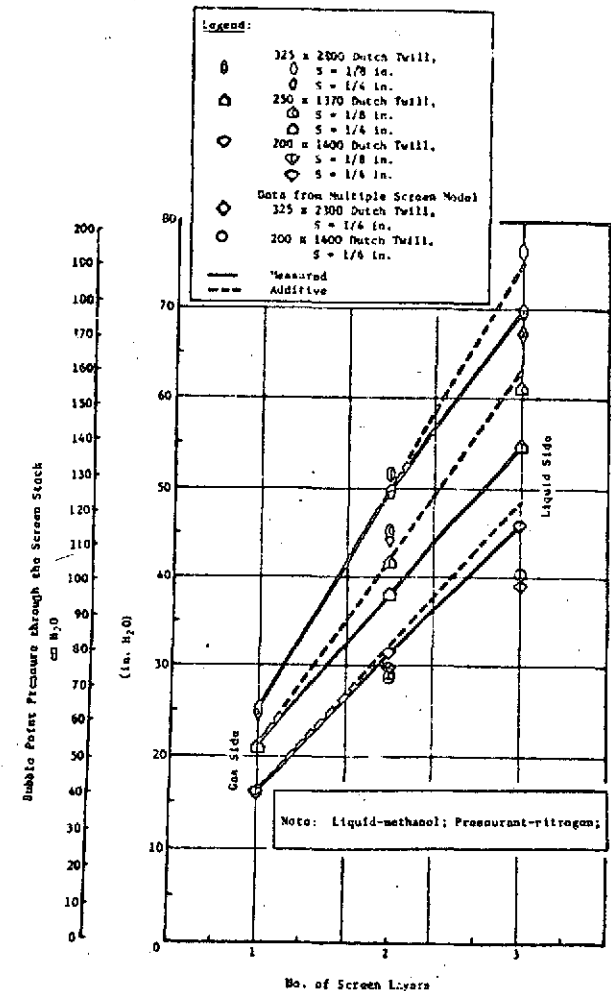 - Thermal Environment Exceeding Predicted

Figure 1. Bubble Point Data from Multiple-Screen Tests

(S = Spacing between screens)

STUDY OF THERMODYNAMIC VENT AND SCREEN BAFFLE
INTEGRATION FOR ORBITAL STORAGE AND TRANSFER OF
LIQUID HYDROGEN
Cady, E.C., MACDAC, NASA CR-134482, MDC G4798,
Contract No. NAS 3-15846, August 1973.

OBJECTIVE. - Experimentally determine the screen bubble point,flow-through pressure
loss, and pressure loss along rectangular channels lined with screen on one side. Using
the correlated experimental data, determine the optimum system characteristics of a
full wall screen liner.

PERTINENT WORK PERFORMED. - Initially, a conceptual tankage design for a
screen liner system integrated with an internal thermodynamic vent system (TVS) was
developed (Figure 1). A comprehensive survey of screens for use in the wall screen
liner was performed. Ten screens were selected based on type of weave, anticipated
bubble point, and pressure drop for flow-through the screen. Bubble point tests were
then conducted for these screens using 3 cm circular specimens bonded with polyurethane
adhesive into a holding fixture. Bubble point testing with isopropyl alcohol was con-
ducted prior to assembly in the LH_2 dewar. All ten samples were mounted together
and were visible through windows at the bottom of the Dewar. With the LH_2 level above
all the specimens, each specimen was pressurized with GH_2 until bubbles appeared.
Pressure differentials were measured with a manometer and a hook gauge. An
apparatus was designed to simultaneously provide flow-through pressure loss data with
channel flow.loss data. Screens were placed normal to the flow in the inlet section and
parallel to the flow in the channel sections as shown in Figure 2. Testing was conducted
using LH_2 saturated at 50 psia. Flow rate was measured with a turbine flow meter and
pressure was measured with a water manometer and a pair of electronic hook gauges.
The tankage system shown in Figure 1 was analyzed for tank sizes ranging from 50 to
5000 ft^3, inflow rates of 1%/min, outflow rates of 1 and 0.01%/min and TVS flowrate
of 1 and 0.1%/min. An optimum weight system was determined for each tank size and
flow rate analyzed.

MAJOR RESULTS. -

1. Bubble point data for the ten screens tested is shown in Table 1. ϕ'ls defined by the
equation $\phi'\sigma / g\rho D = H$ where H is the supported head.

2. Flow loss correlations for flow normal to the screens tested are tabulated in Table 2.

3. Friction factors for the screens obtained from the channel flow test data, correlated
fairly well with the relative roughness and Reynolds number as depicted by Moody
graphs presented in Appendix B of the report for each of the screens tested.

4. Maximum screen liner performance was obtained with 325×2300 screen, but for
some cases 150×150 screen provided the lowest weight system. For long duration
missions (300 days) pump efficiency was very important because pump boiloff became
the design driver.

Table 1. Alcohol and 34.5 N/cm^2 (50 psia) LH$_2$ Bubble-Point Test Data

Screen (wire dia)	Pre LH$_2$ test alcohol data		Post LH$_2$ test alcohol data		LH$_2$ data	D	φ
	Measured bubble point in inches H$_2$O (standard)	Predicted bubble point in meters of 34.5 N/cm^2 (feet of 50 psia) LH$_2$	Measured bubble point in inches H$_2$O (standard)	Predicted bubble point in meters of 34.5 N/cm^2 (feet of 50 psia) LH$_2$	Bubble point in meters of 34.5 N/cm^2 (feet of 50 psia) LH$_2$	Manufacturer's Rated Absolute pore size (microns)	
325 x 2,300 (0.0015/0.001)	23.90	0.5090 (1.670)	21.60	0.4602 (1.510)	0.4815 (1.580)	10	2.66
200 x 1,400 (0.0028/0.0016)	16.55	0.3523 (1.156)	16.51	0.3517 (1.154)	0.3377 (1.108)	14	2.60
500 x 500 (0.001)	7.73	0.1646 (0.540)	7.75	0.1652 (0.542)	(0.1704)a 0.1464 ((0.559)a (0.479b))	25.4	(2.39)a 2.05b
720 x 140 (0.0014/0.0043)	7.82	0.1664 (0.546)	7.82	0.1664 (0.546)	0.1767 (0.580)	26	2.53
165 x 800 (0.0029/0.0020)	6.70	0.1428 (0460) (0.471)	6.75	0.1436 (0.471)	0.1226 (0.403)	36	2.44
50 x 250 (0.0055/0.0045)	3.45	0.07346 (0.241)	3.38	0.0719 (0.236)	0.0682 (0.224)	65	2.45
150 x 150 (0.0026)	2.25	0.0480 (0.1575)	2.26	0.04816 (0.1580)	0.0460 (0.1510)	103	2.62
24 x 110 (0.015/0.0105)	1.685	0.0359 (0.1178)	1.695	0.03612 (0.1185)	0.0336 (0.1105)	155	2.88
60 x 60 (0.0075)	0.998	0.02121 (0.0696)	0.996	0.02118 (0.0695)	0.0230 (0.0754)	233	2.95
40 x 40 (0.010)	0.620	0.01323 (0.0434)	0.625	0.01332 (0.0437)	0.0170 (0.0559)	381	3.58

a General breakdown
b Single wire breakdown
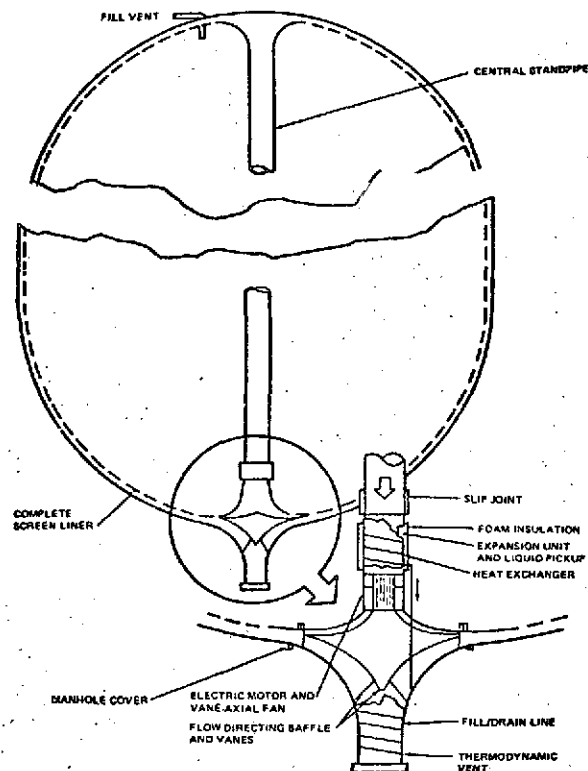
Table 2. Flow Loss Correlation

Screen	D, m (ft)	a, 1/m (1/ft)	b, m (ft)	ε	Armour and Cannon Form $f = \frac{a}{R} + \beta$		H = AV + BV^2 H in m of 34.5 N/cm^2 LH$_2$ V in m/sec		H in ft of 50 psia LH$_2$ V in ft/sec	
					α	β	A	B	A	B
325 x 2,300	0.000005 (0.0000164)	110,235 (33,592)	0.000089 (0.000292)	0.245	3.2	0.19	1.14	0.6919	1.14	2.27
200 x 1,400	0.000010 (0.0000328)	65,390 (19,930)	0.0001524 (0.0005)	0.248	4.2	0.20	0.885	0.6126	0.885	2.01
720 x 140	0.000015 (0.0000492)	32,954 (10,044)	0.0001804 (0.000592)	0.514	11.0	0.47	0.162	0.2627	0.162	0.862
165 x 800	0.000026 (0.000082)	41,360 (12,606)	0.0001753 (0.000575)	0.426	3.3	0.17	0.108	0.0805	0.108	0.264
50 x 250	0.00005 (0.000164)	13,075 (3,985)	0.000369 (0.00121)	0.611	13.5	0.26	0.045	0.0631	0.045	0.207
24 x 110	0.000115 (0.000377)	5,889 (1,795)	0.000914 (0.003)	0.572	8.61	0.52	0.0165	0.1554	0.0165	0.51
500 x 500	0.0000254 (0.0000833)	65,495 (19,962)	0.0000509 (0.000167)	0.584	5.7	0.65 (0.77)a	0.0554	0.03298 (0.04267)a	0.0554	0.1082 (0.140)a
150 x 150	0.000103 (0.000339)	19,916 (16,070)	0.000132 (0.000433)	0.671	5.7	0.50 (0.50)a	0.0101	0.01347 (0.01347)a	0.0101	0.0442 (0.0442)a
60 x 60	0.000233 (0.000764)	(8,137) (2,480)	0.000381 (0.00125)	0.612	5.7	0.40 (0.61)a	0.00585	0.01820 (0.02761)a	0.00585	0.0597 (0.0906)a
40 x 40	0.000381 (0.00125)	5,328 (1,624)	0.000509 (0.00167)	0.662	5.7	0.60 (0.52)a	0.00287	0.01728 (0.01497)a	0.00287	0.0567 (0.0491)a
					8.61	0.52				

a Based on $Eu = \left(\frac{S}{1-S}\right)^2$

Figure 1. Conceputal Tankage Design
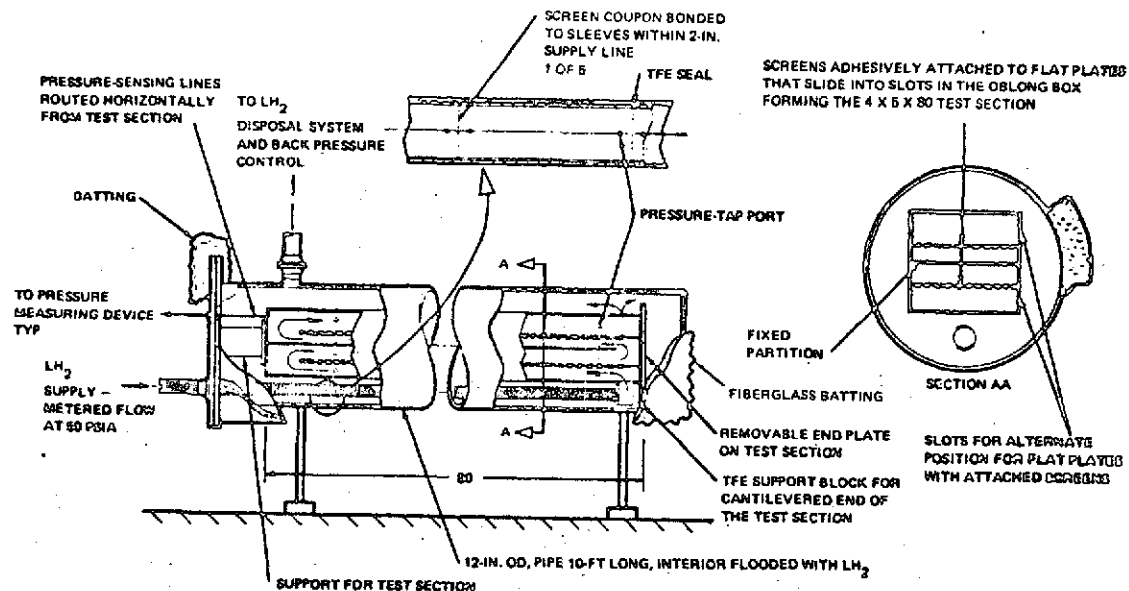
Figure 2. Flow-Loss Test Apparatus

ACQUISTION/EXPULSION SYSTEM FOR EARTH ORBITAL SYSTEM
STUDY, FINAL REPORT - Volume II Cryogenic Design
Paynter, H.L., Page, R.G, MMC, MCR-73-97
NAS9-12182, June 1973

OBJECTIVE. - Design passive acquisition/expulsion systems for subcritical storage of cryogens in the Space Shuttle Orbiter and the Space Tug propulsion systems.

PERTINENT WORK PERFORMED. - The dual screen liner (DSL) approach was chosen as the baseline for this study. The basic DSL concept, shown in Figure 1, was designed to provide liquid free vapor in the outer annulus for venting, vapor free liquid for expulsion between the two spherical screens and near continuous control of the bulk propellant in the inner sphere. Venting of the vapor annulus must be performed within the bubble point of the outer screen liner in order to assure that liquid does not enter this region during venting. Communication screens, with lower bubble point than the screen liners, are used to vent the inner sphere to the outer annulus. A channel/liner system was examined for reducing residuals. The system relies upon wicking to keep the liner wet between channels. The channels replace the liquid annulus. Use of a weeping tank concept with a permeable membrane vented to vacuum, to control pressure over a wider pressure band than the basic DSL concept was considered. The DSL concept was also applied to cryogenic feedlines as shown in Figure 2.

Information was presented in four basic categories related to cryogenic acquisition system evaluation and design: (1) Fluid Mechanics (2) Thermal and Thermodynamics (3)Structures and (4)Configuration and Size. Computer models were constructed to predict outflow capability and used to generate parametric data. Subscale DSL tests conducted with noncryogens on the KC-135 aircraft qualitatively demonstrated system expulsion capability. Analyses were conducted for evaluating start transients, screen and screen/perforated plate wicking, tank pressurization and venting, pressurization system characteristics, stratification, vent system characteristics, vapor bubble collapse and weeping tank thermal performance. Structural evaluations included analysis of unsupported screen deflection, cyclic induced screen structural fatigue, and screen cleaning. Foraminous material properties were tabulated. Designs were presented for the cryogenic fueled Space Shuttle Orbital Maneuvering System (OMS)/Reaction Control System (RCS) and dedicated OMS as well as for the space tug.

MAJOR RESULTS. -

1. Bubble collapse times computed for LH_2 and LO_2 are shown in Figure 3.

2. Screen to screen joining and screen to plate joining were accomplished with spot welding, brazing and soldering. Welding is the superior method.

3. Series feed tankage was selected over parallel feed tankage based on lower weight and complexity.

4. A development plan was presented including an orbital test program (see Tables VI-1 to VI-4 of the report).
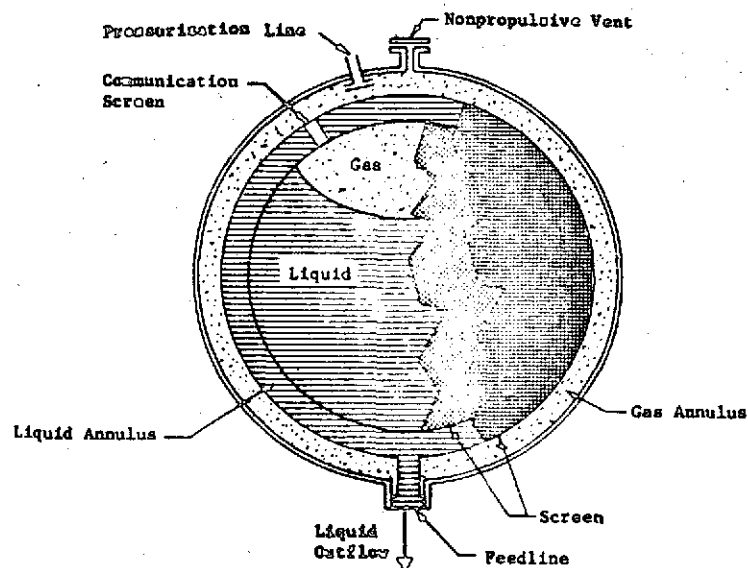
Figure 1. Basic DSL Concept
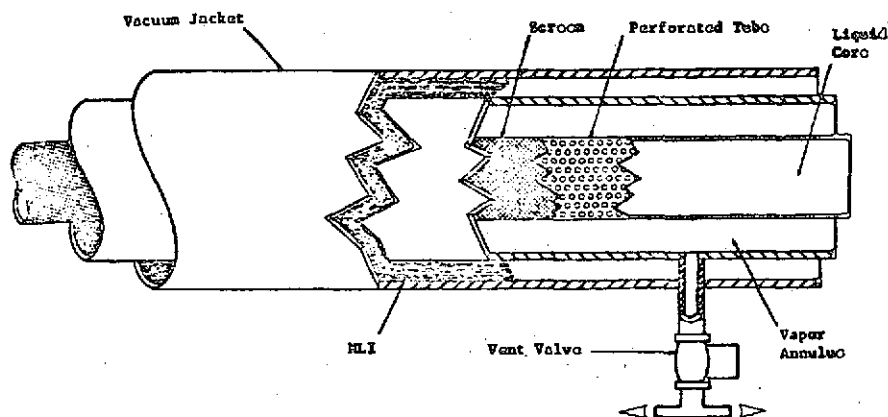
Figure 2. Screen Liner Cryogenic Feedlines
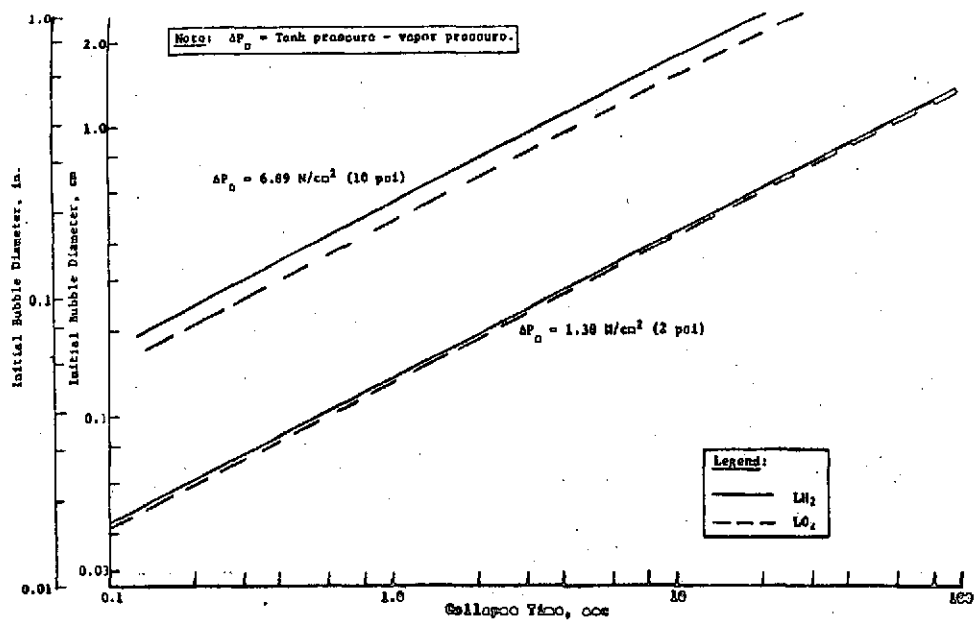
Figure 3. Collapse Time for Spherical Vapor Bubble in Subcooled
Liquid (Prisnyakov)

11-17

ACQUISITION/EXPULSION SYSTEM FOR EARTH ORBITAL
SYSTEM STUDY, FINAL REPORT, VOLUME III,
CRYOGENIC TEST
Paynter, H.L., Page, R.G., MMC,
MCR-73-97, NAS9-12182, June 1973

OBJECTIVE. - Verify cryogenic system design for the dual screen liner (DSL) concept
with subscale ground tests.

PERTINENT WORK PERFORMED. - Low g tests were conducted in a KC-135 using
plexiglas models and noncryogenic fluids. These tests evaluated DSL expulsion, bubble
collapse, and capillary pumping. One g bench tests were run to determine multilayer
screen layer bubble point, temperature dependency of bubble point in LN_2 and LO_2,
vapor flow pressure loss across wetted screen and screen/plate barriers, prevention
of screen breakdown while venting within a ΔP band, screen/plate wicking, fine mesh
screen structural capability, nonvisual bubble point test techniques, feedline screen
liner operation and vibration effects on screen retention. Tests were conducted on a
DSL in a 25 in. diameter spherical tank (Figure 1) using liquid hydrogen and liquid
nitrogen as test fluids.

MAJOR RESULTS. -

1. Except for some bubbles observed during flow initiation,the low gravity aircraft
   tests demonstrated low-g,gas free liquid expulsion. The initial gas ingestion
   occurred because of vapor trapped in the device during high g loadings.

2. Bubble collapse test data compared fairly well with theoretical collapse time pre-
   dicted by $\gamma = 1 - 2 \epsilon / \tau_H$ (see Table 1 for nomenclature)

3. Multilayer screen layers must be maintained in a wetted condition using wicking or
   capillary pumping in order to provide additive bubble points.

4. Screen bubble point depends upon temperature, as shown in Figure 3.

5. Lower vapor flow pressure drops occur for wetted screen/perforated plate than for
   wetted screen alone. (Figure 2).

6. Bubble point-rewetting tests indicate that once vapor penetrates a wetted screen,
   pressure drop must be dropped to 57% of the bubble point to assure rewetting and
   resealing of the screen.

7. Order of magnitude increases in wicking distance were obtained for screen/plate
   combinations compared to screen alone.

8. For sinusoidal vibration tests, retention failure corresponded to model resonance,
   Hydrostatic analysis successfully predicted screen retention capability during
   random vibration.

9. Cryogenic tests successfully demonstrated DSL expulsion capability in - lg with both
   cold and warm gas pressurization. Venting could not be successfully demonstrated
   because of adverse thermal stratification.
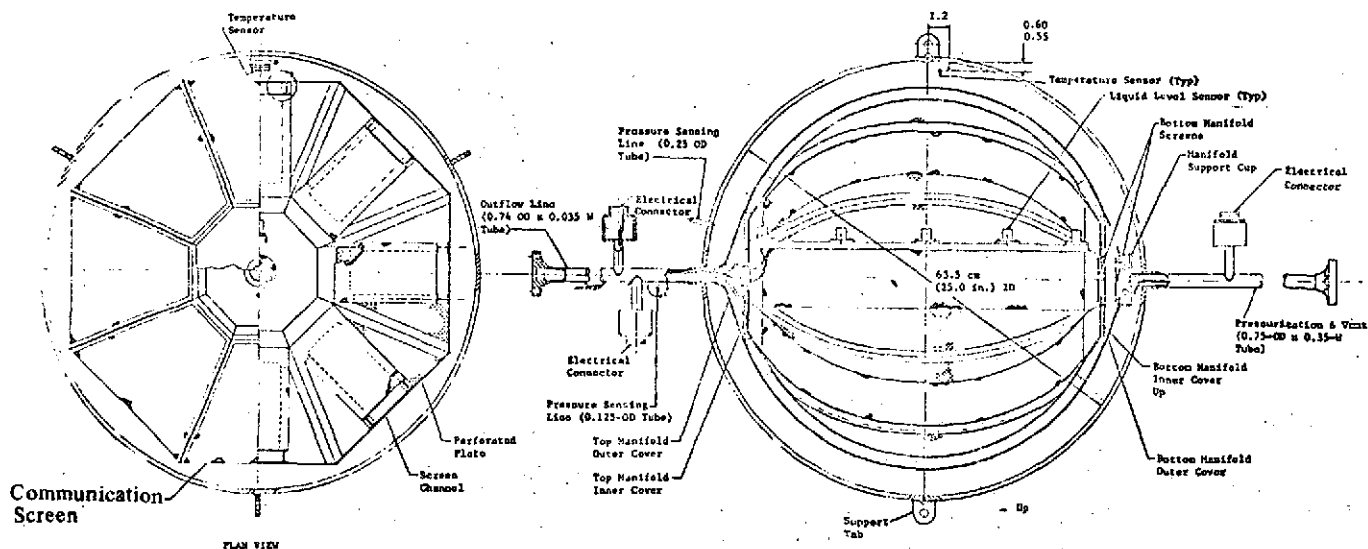
Figure 1. Assembly Dwg for 63.5 cm (25 in.) Subscale Model
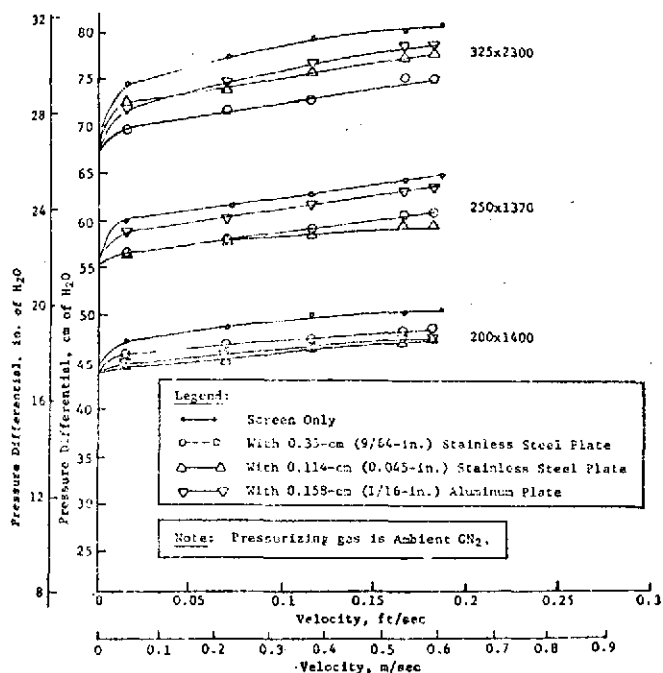
Figure 2. Methanol Screen and Perforated Plate Data Adjusted to Common Bubble Point
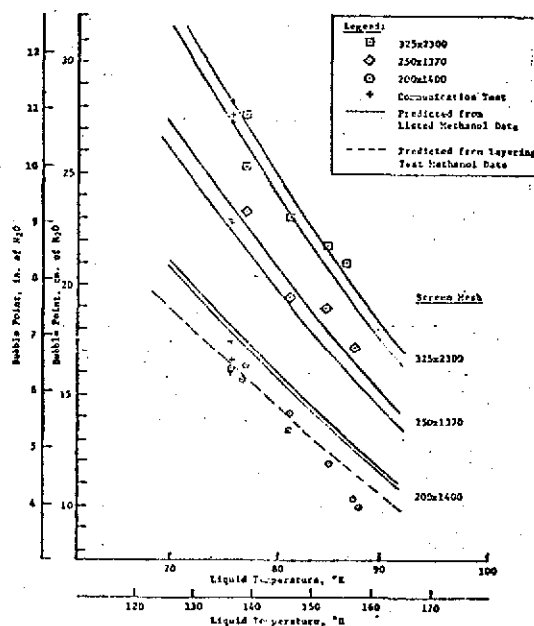
Figure 3. Effect of Temperature on Pressure Retention Capability in Nitrogen

Ja = Jacob No., $(\rho_{\ell} C_p \Delta T)/(\rho_V \lambda)$

r = bubble radius

r_0 = bubble radius at time t = 0

t = time

α = thermal diffusivity of liquid

γ = r/r_0, nondimensional radius

ΔT = $T_{sat} - T_{\ell}$

ϵ = $1 + \rho_V/\rho_{\ell} (2Ja-1)$

λ = latent heat of evaporation

ρ_V = vapor density

ρ_{ℓ} = liquid density

τ_H = $\frac{4}{\pi} Ja^2 \frac{\alpha t}{r_0^2}$

Table 1. Nomenclature

11-19

SELECTION OF A SURFACE TENSION PROPELLANT
MANAGEMENT SYSTEM FOR THE VIKING 75 ORBITER
Dowdy, M. W. (JPL), DeBrock, S. C. (LMSC), AIAA Paper
No. 72-1042, November 1972

OBJECTIVE. - Select a surface tension propellant management system for the Viking
75 Orbiter.

PERTINENT WORK PERFORMED. - Mission requirements were analyzed in order to
provide gas free propellant to the engine and to position propellant symmetrically about
each tank centerline for spacecraft center of mass control. The entire device had to
be installed and removed through a 9 in. drain access hole. Several candidates (Figure
1) were evaluated with the selection rapidly narrowed to a choice between truncated
central cross and a central baffle concepts. Both concepts act to position propellant
over the outlet, drive the ullage bubble radially outward and forward, locate the
propellant center of mass on the tank axis, stabilize the ullage bubble on the tank center-
line at the forward end of the tank to reduce disturbance during pressurization, and
provide vent port access to the vapor for relief valve depressurization of the tanks.
The central baffle concept, while structurally more complicated, was selected over the
central cross because of its greater ability to control the ullage and minimize slosh
disturbances. A typical mission operational sequence is shown for the central baffle
design in Figure 2.

The baffles are configured to cause vapor to move to an equilibrium position near the
vent. This is illustrated in Figure 3 where the force driving the bubble to its equilibrium
position is shown as a function of location along the tank centerline. Bubble motion,
caused by reorientation or disturbing accelerations, is damped by the surface forces
between the contained fluid and the solid surfaces. An extended tube arrangement
was selected for the pressurization/vent tube. A capillary channel of 0.01 in^2 cross
sectional area, conforming to the inside of the tank, was used for capillary pumping of
condensate from the cold forward end of the tank to the warm forward end.

A development test program was proposed using a functional matrix chart that is
difficult to understand. (Much of this material was presented in Debrock, 1973).
A spherical tank baffle device was designed, fabricated from pure titanium sheet, and
subjected to low frequency slosh vibrations in a 30 in. diameter plastic tank. Baffle
elements were able to withstand the imposed structural loading. A furling tool was
also designed and fabricated for installing a one piece baffle through a small propellant
tank access hole.

MAJOR RESULTS. -

1. A passive design for providing fluid center of mass, vapor free liquid outflow and
   liquid free vapor for venting was developed.

2. Fabrication and structural evaluation studies indicated the feasibility of the
   crossed baffle design.

11-20
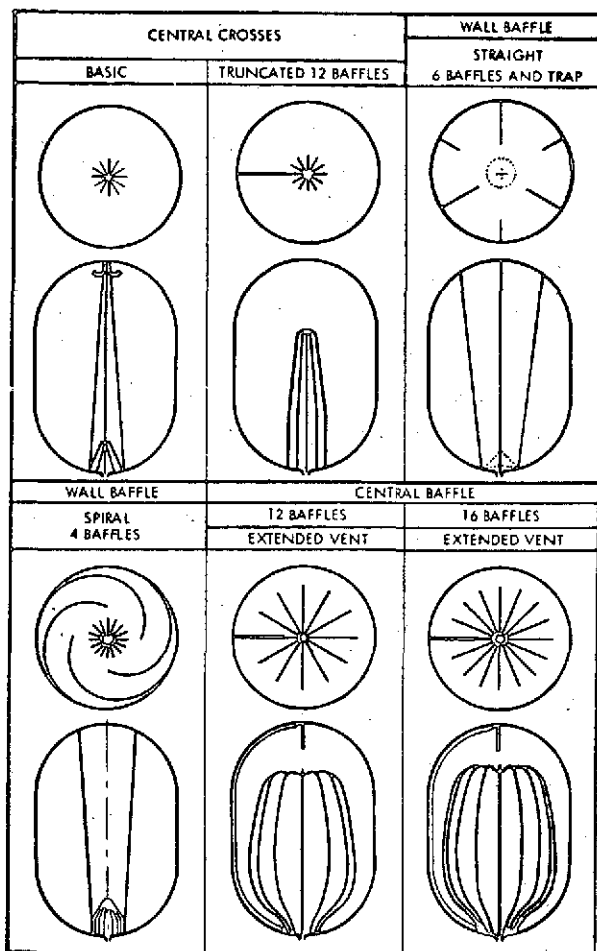
Figure 1. Candidate Concepts
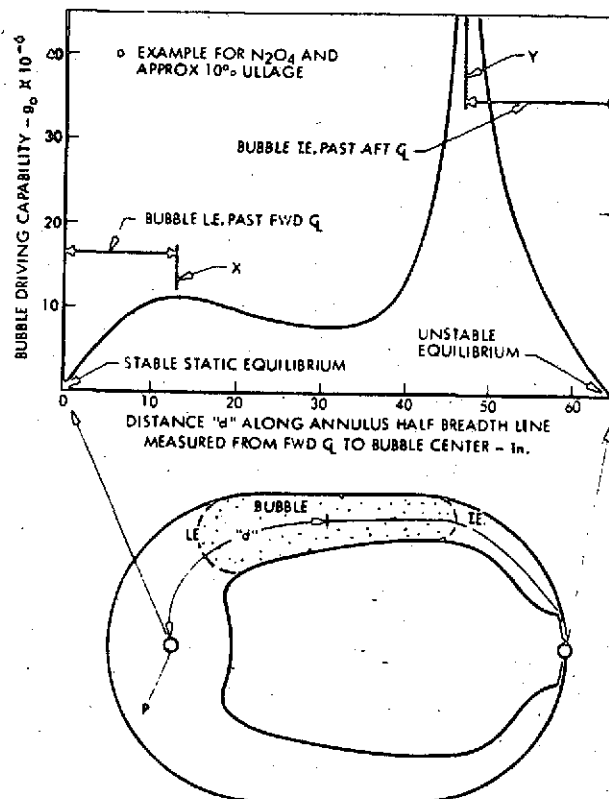
Figure 3. General Profile of Baffle Driving Capability
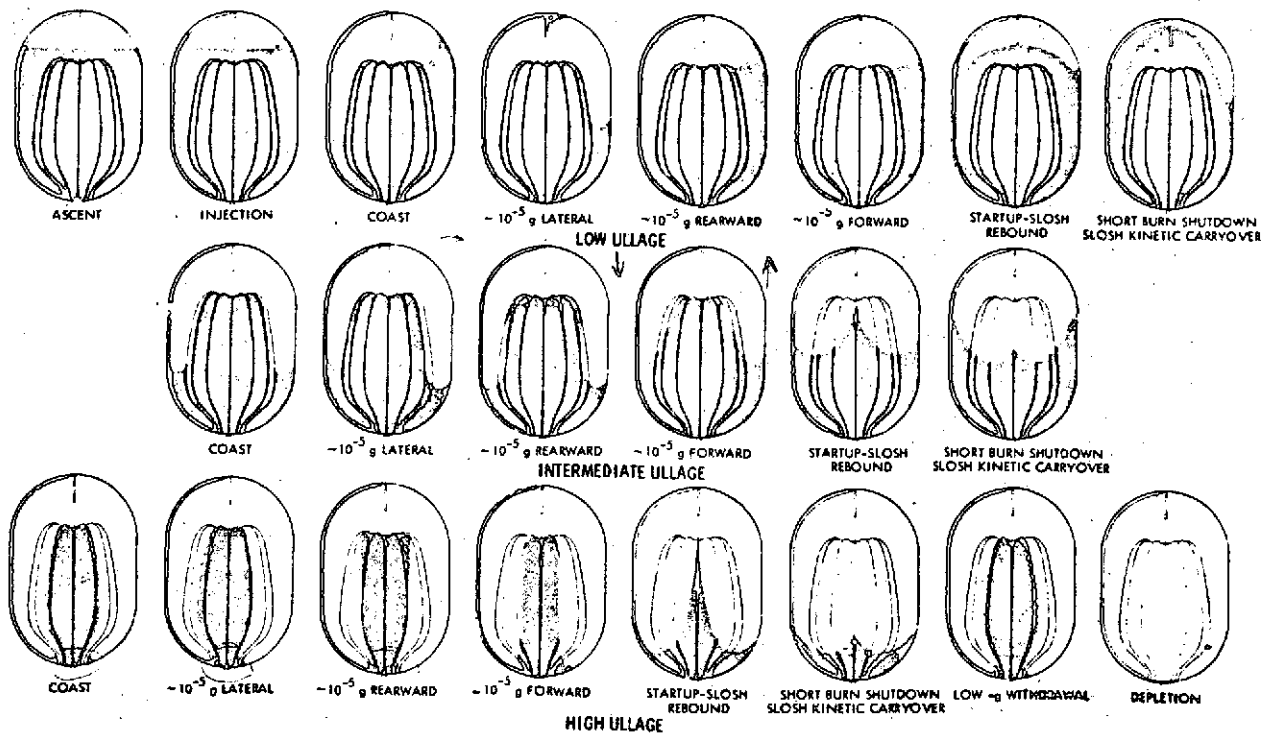
Figure 2. Typical Operating Sequence of Viking Propellant Management

11-21

AN INTEGRATED START TANK FOR CRYOGENIC
PROPELLANT CONTROL
Blackmon, J.B., Castle, J.N., MACDAC, 12th JANNAF Liquid
Propulsion Meeting, Nov. 1970

OBJECTIVE. - Develop the preliminary design of an integrated start tank/screen
retention system, and compare this system with settling techniques and other
capillary acquisition systems.

PERTINENT WORK PERFORMED. - An LH_2 start tank composed of off-the-shelf
hardware was designed consisting of an auxiliary pressure vessel containing a screen
retention device located in the main propellant tank with one fill and one vent valve
as shown in Figure 1. The design is integrated with a thermodynamic vent system.
The start tank provides; quick restart, good thermal protection of the screen retention
device, refill ability at low and high g, normal gravity checkout capability, and liquid
inlet for a thermodynamic vent system. Warm helium pressurization is employed
for the main liquid hydrogen tank and cold helium for the start tank. Operationally,
the start tank provides liquid delivery to the feedline and main engines. Main engine
thrust settles the propellant. The main tank is pressurized to 2 to 3 psi greater than
the start tank after liquid has cleared from the top of the tank. After the main tank is
settled, the start tank refill and vent valves are opened and the main tank fluid refills
the start tank while supplying engine outflow. Between burns, a vapor bypass line is
provided in the feedline to vent vapor back to the start tank, maintaining the feedline
full of liquid. Vacuum refill was described for refilling the start tank in low-g.
Pressure rise rate curves for the start tank were utilized to determine thermal
conditioning requirements. A small scale model ground demonstration start tank was
fabricated and successfully fluid dynamically tested using water as the test fluid.
Settling and refill were simulated using a large ballon to initially hold liquid away
from the start tank. Breaking the ballon initiated settling. Settling work reported
is similar to Blackmon et al, 1968.

MAJOR RESULTS. -

1. The major advantages of the start tank compared to partial and total control
   screen devices are more direct pressure and screen control and small head
   requirements for the screen retention surfaces.

2. The start tank hardware weight is higher than a start basket but the pressurization
   system weight is lower since hot gas pressurization may be used in the main tank
   when a start tank is employed for settling the main tank liquid.

3. Start tank weight estimates as a function of volume are shown in Figure 2.

COMMENTS. - Figure 2 is presented merely to illustrate the general weight trend of
start tank components. Burge and Blackmon, 1973 gives more detail weight breakdowns.
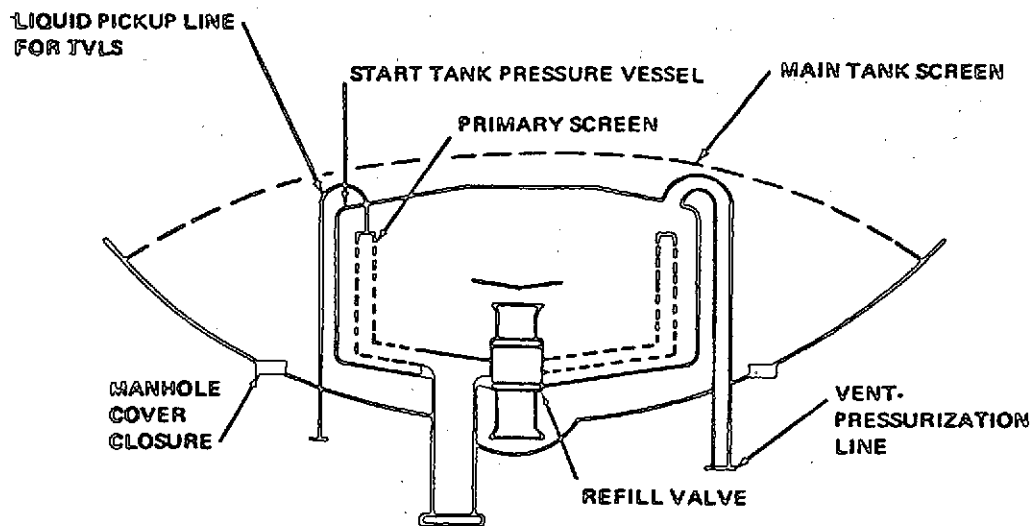
Figure 1. MDAC Start Tank Schematic
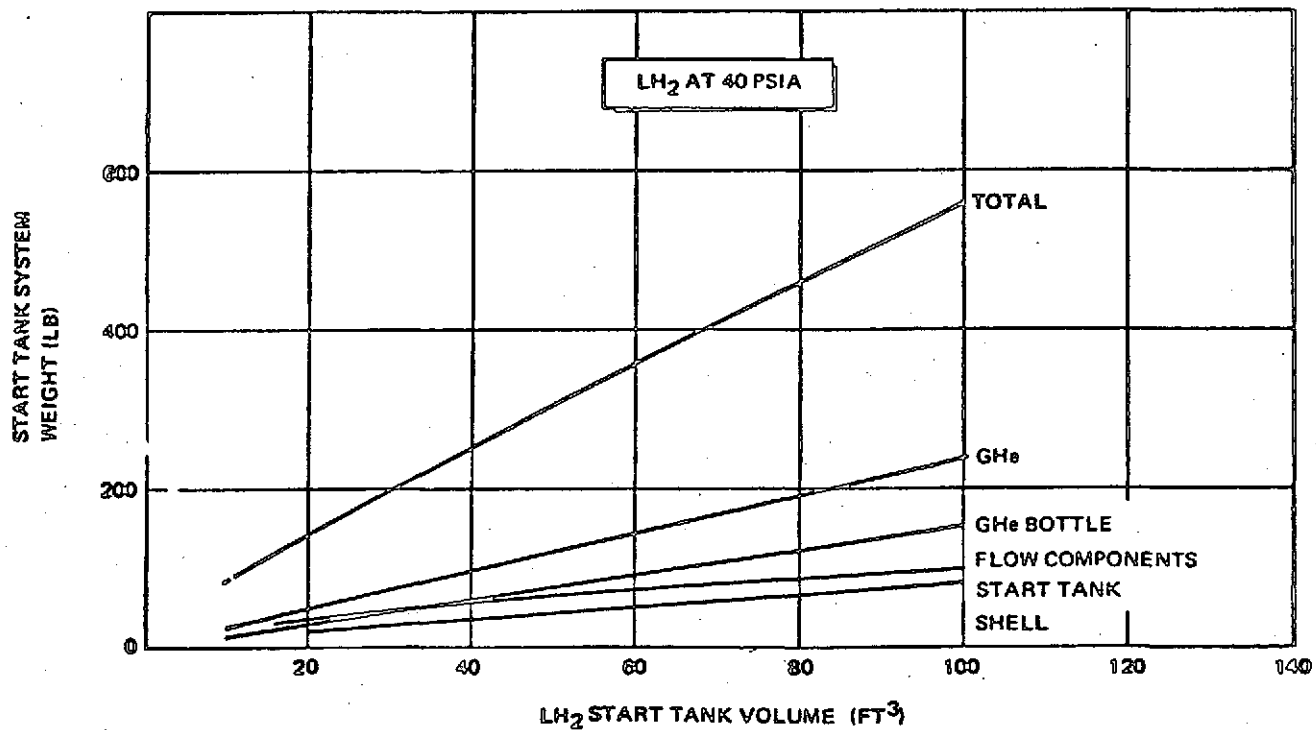
Figure 2. Start Tank Volume (Ft^3)

11-23

SIMULATED FLIGHT VIBRATION TESTING OF A SURFACE
TENSION PROPELLANT EXPULSION SCREEN
Orton, G.F., MACDAC, 12th JANNAF Liquid Propulsion
Meeting, October 1970

OBJECTIVE. - Experimentally determine the effect of flight vibration environments
on the performance of a spherical surface propellant expulsion screen.

PERTINENT WORK PERFORMED. - An 11.6 inch diameter spherical test screen of
pleated 250 × 1370 mesh 304L stainless steel dutch twill wire cloth was mounted in
a spherical Plexiglas test tank. The tank screen assembly was mounted to an exciter
capable of a 5-2000 Hz frequency range and a one-inch peak-to-peak stroke. The fluid
outlet was at the top of the tank. Testing was conducted using isopropyl alcohol and
Freon 113. Simulated launch vibration tests using both sinusoidal and random vibration
were conducted. Specific conditions run for each test are specified in Table 1. Operating
vibration tests were conducted by imposing random vibration levels on the test model as
tabulated in Table 2. Frequency was increased as a function of time for both launch and
operating vibration tests. Data was evaluated by summing the gravitational and vibra-
tional acceleration vectorially and comparing the resultant pressure differential due to
acceleration with the pressure retention capability of the screen.

MAJOR RESULTS. -

1. Screen retention capability was evaluated in Figure 1 for low frequency range vertical
   sinusoidal vibrations by comparing the pressure differentials during vibration to the
   retention pressure, ΔP_σ, where $\Delta P_\sigma = \phi\ (2\sigma/d)$. (d is the bubble point of 17 microns
   and ϕ is normally assumed to be 1.36). At low frequency, data agreed fairly well
   with theory.

2. Large pressure differentials, compared to the retention pressure were required to
   produce retention failure when using low frequency lateral sinusoidal vibrations.

3. High frequency range data indicates that, above a threshold frequency simple hydro-
   static theory is insufficient for predicting screen performance under sinusoidal
   vibration. Retention was maintained even though peak pressure due to accelerations
   were above the bubble point pressure. The author postulated that this was caused by
   surface elasticity effects or reduced transmissibility due to gas bubbles trapped
   between the screen and the tank wall.

4. Screen resonant frequency was found to vary directly with screen pressure differential
   (Figure 2). Violent screen failure at high frequency was attributed to screen resonance.

5. Hydrostatic theory appeared to predict performance during random vibration tests.

COMMENTS. - This work illustrated that additional testing was required in improving
upon hydrostatic theory and in investigating screen resonance.

11-24

Table 1. Simulated Launch Vibration Test Matrix

TEST FLUID: ISOPROPYL ALCOHOL

TEST NO.	HYDROSTATIC HEAD	TANK PRESSURE	AXIS	MODE	LEVELS	FREQUENCY
1	5.71 IN.	25 PSIA	VERTICAL	SINUSOIDAL	0.2 IN. DA* TO 5 G PEAK	5-300 Hz
2	6.99					5-300 Hz
3	8.38					5-30 Hz
4	7.28					5-12 Hz
5	11.00				0.2 IN. DA* TO 5 G PEAK	5-11.5 Hz
6	11.05				0.003 IN. DA TO 2.06 G PEAK	5-300 Hz
7	10.50			SINUSOIDAL	0.141 IN. DA TO 3.53 G PEAK	5-300 Hz
8	11.59			RANDOM	7 G RMS	50-2000 Hz
9	5.99					
10	1.55		VERTICAL	RANDOM	7 G RMS	50-2000 Hz
11	6.73		LATERAL	SINUSOIDAL	0.2 IN. DA TO 5 G PEAK	5-300 Hz
12	7.00					
13	8.3					
14	9.35					
15	10.7				0.2 IN. DA TO 5 G PEAK	5-300 Hz
16	9.3				0.083 IN. DA TO 2.06 G PEAK	5-23 Hz
17	9.3			SINUSOIDAL	0.141 IN. DA TO 3.53 G PEAK	5-100 Hz
18	10.7			LATERAL	RANDOM	7 G RMS	50-2000 Hz

TEST FLUID: FREON 113

TEST NO.	HYDROSTATIC HEAD	TANK PRESSURE	AXIS	MODE	LEVELS	FREQUENCY
19	1.17		VERTICAL	SINUSOIDAL	0.072 IN. DA TO 1.02 G PEAK	5-600 Hz
20	2.26					
21	3.36					
22	4.20					
23	5.60				0.072 IN. DA TO 1.02 G PEAK	5-200 Hz
24	5.47			SINUSOIDAL	0.05 IN. DA TO 0.91 G PEAK	5-300 Hz
25	2.23			RANDOM	1.1 G RMS	50-2000 Hz
26	1.00	25 PSIA	VERTICAL	RANDOM	1.1 G RMS	50-2000 Hz

*DA = DOUBLE AMPLITUDE

Table 2. Operating Vibration Test Matrix

TEST NO.	TEST FLUID	TANK PRESSURE	FLOW RATE	AXIS	MODE	LEVEL	FREQUENCY
27	ISOPROPYL ALCOHOL	30 PSIA	0.55 LB/SEC	VERTICAL	RANDOM	4.55 G RMS	50-2000 Hz
28	ISOPROPYL ALCOHOL	30 PSIA	1.00 LB/SEC	VERTICAL	RANDOM	4.55 G RMS	50-2000 Hz
29	ISOPROPYL ALCOHOL	30 PSIA	0.43 LB/SEC	LATERAL	RANDOM	4.55 G RMS	50-2000 Hz
30	FREON 113	30 PSIA	0.66 LB/SEC	VERTICAL	RANDOM	2.0 G RMS	50-2000 Hz
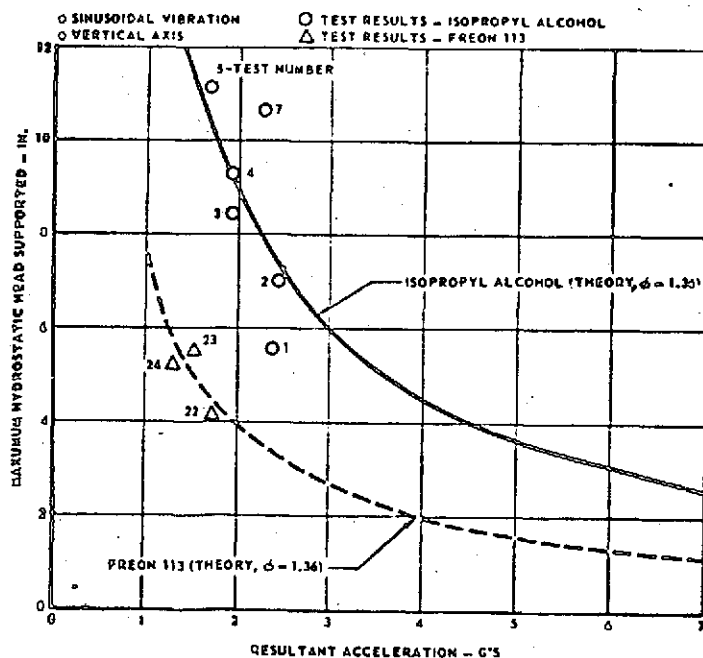
Figure 1. Comparison of Theory and Test Results
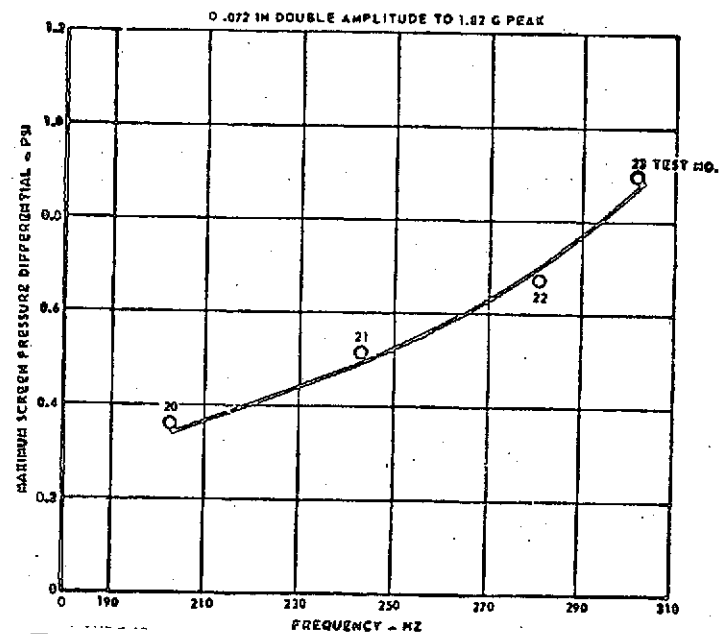
Figure 2. Frequency–Pressure Correlation for Screen Resonance

LOW GRAVITY PROPELLANT CONTROL USING CAPILLARY
DEVICES IN LARGE SCALE CRYOGENIC VEHICLES, PHASE I
FINAL REPORT, Blatt, M. H., et al, GD/C, GDC-DDB70-007,
NAS8-21465, August 1970.

OBJECTIVE. – Determine the feasibility of using cryogenic capillary devices for low
gravity propellant control.

PERTINENT WORK PERFORMED. – Two missions were considered; a single restart
mission for the LO_2/LH_2 S-IVC and a propellant transfer mission using a LOX tank-
er to fill an S-IIB.

Capillary devices were designed based on fluid and thermal analysis. The fluid analy-
sis considered screen pressure drop, retention, settling spilling, vapor ingestion, re-
filling and venting. The thermal analysis considered both passive and active means
for preventing vapor formation from within the capillary devices.

Bench tests were run using pentane and dutch twill (wicking) and square weave (non-
wicking) screens of similar bubble point to qualitatively determine the retention capa-
bility of capillary burners subjected to evaporation.

Capillary device designs developed were compared to bladders, dielectrophoresis,
and linear acceleration on the basis of cost, reliability, weight and manufacturing fea-
sibility. Because of the uncertainty in predicting settling time for S-IVC conditions,
comparisons were made over a range of settling times.

MAJOR RESULTS. –

1. The venting analysis demonstrated that significant quantities of vapor could be
   formed in the capillary device if pressure was not controlled within a narrow band.
   A thermodynamic vent system can be used for this purpose as well as to cool the
   capillary device and feedline.

2. The settling analysis demonstrated the importance of geysering, recirculation and
   turbulent dissipation when employing high Bond number settling.

3. Wicking screens have better retention capabilities than nonwicking screens when
   subjected to evaporation.

4. The LOX tanker system capillary design (Figure 1) compared favorably with other
   means of propellant control (Table 1). Bladders, although slightly lower in weight
   have permeability problems with cryogens and possible LO_2 impact problems.

5. The S-IVC LO_2 and LH_2 start baskets compared favorably with other means of
   propellant control (Figure 2).
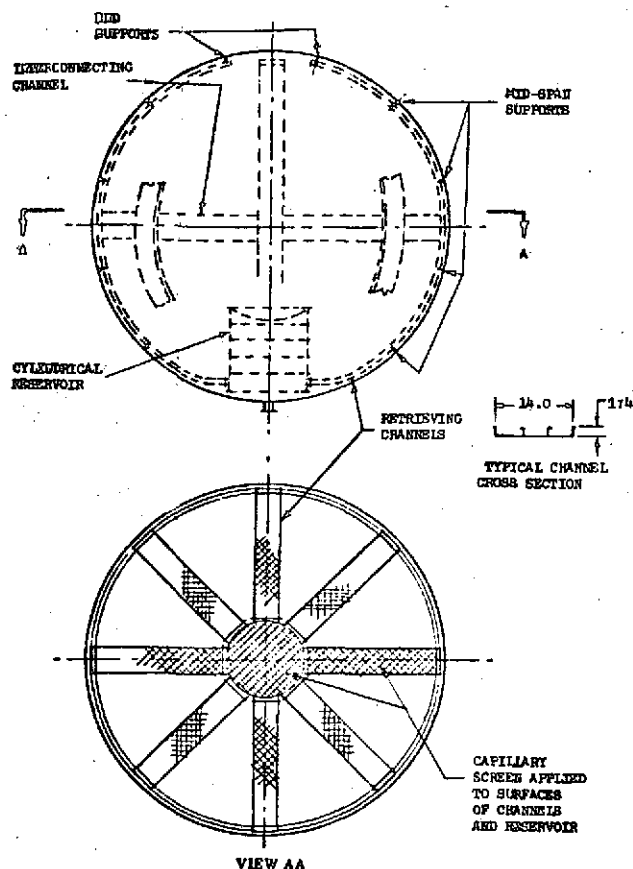
Figure 1. Oxidizer Collector System
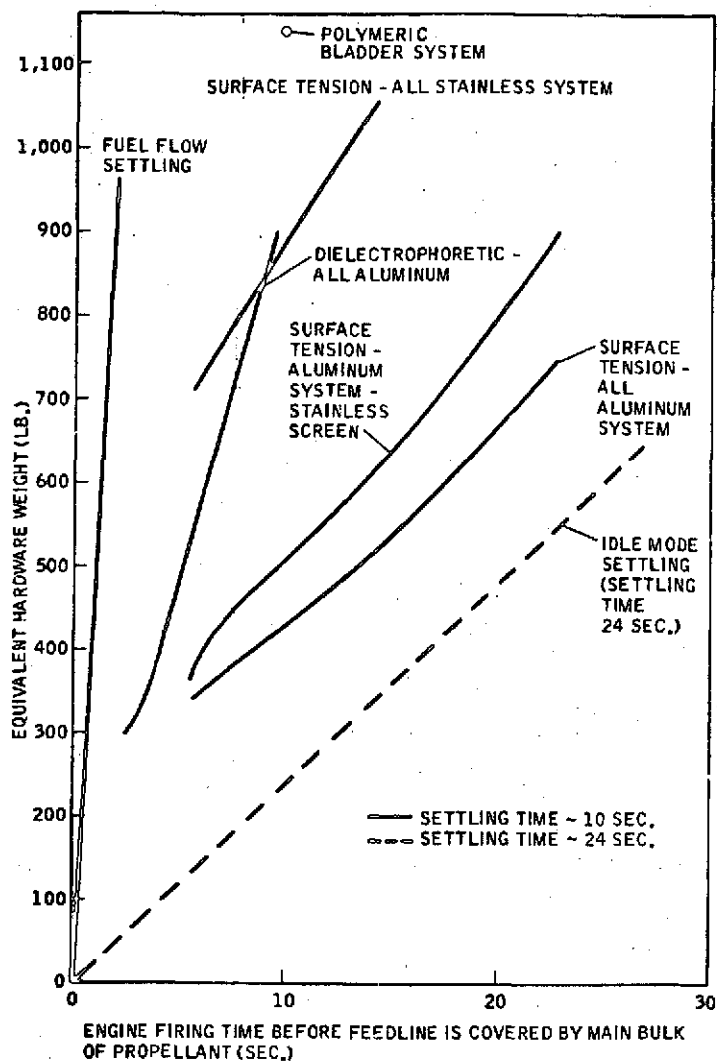
Figure 2. Equivalent Hardware Weight Comparison for S-IVC Mission Restart

Table 1. LO$_2$ Tanker Weight Comparisons

TYPE OF PENALTY	SETTLING	SETTLING WITH SCAVENGING	ALUMINUM SURFACE TENSION (CHANNELS)	ALUMINUM SURFACE TENSION CHANNELS (STAINLESS SCREENS)	STAINLESS SURFACE TENSION (FULL LINER)	DIELECTRO-PHORESIS	BLADDER	ALL STAINLESS (SURFACE TENSION CHANNELS)
VENT SYSTEM	10	10	25	25	50	10	10	2
TRANSFER SYSTEM	100	100	417	522	685	488	163	828
RESIDUALS	1,883	33	33	33	33	33	925	33
SECONDARY PROPULSION	700	1,467	777	777	777	777	-	777
ADDED PRESSURANT	-	-	-	-	-	-	30	-
	2,693	1,610	1,252	1,357	1,512	1,308	1,128	1,663

LOW GRAVITY PROPELLANT CONTROL USING CAPILLARY
DEVICES IN LARGE SCALE CRYOGENIC VEHICLES, PHASE II
FINAL REPORT, Blatt, M. H., et al, GD/C, GDC-DDB70-008
NAS8-21465, August 1970

OBJECTIVE. - Analytically and experimentally evaluate fluid and thermal problems
associated with cryogenic capillary propellant control devices.

PERTINENT WORK PERFORMED. - Fluid analysis of the S-IVC and LOX tanker
missions (see Blatt, et al, Phase I, 1970) consisted of capillary device outflow,
liquid settling, wicking, vapor impingement and refilling. Computer programs were
formulated for analysis of wicking and outflow in order to correlate experimental
data. Thermal analysis was devoted to detailed sizing of capillary device cooling
configurations and consideration of destratification and mixing effects on cooling system
operation. Systems designed for both missions used the normal boiloff capability of
a thermodynamic vent system to maintain the contained liquid in a slightly subcooled
condition. The feedline was maintained filled with liquid up to a conical screen
barrier near the engine. The structural design effort consisted of developing weight
estimates, support, attachment and cooling configuration details along with load
analysis and assembly drawings. Normal gravity bench tests were conducted to evaluate
capillary device draining, spilling and outflow in transparent scale model S-IVC
tankage. Pullthrough suppression tests were run in simple cylindrical containers to
verify the analytical procedures used for sizing pullthrough suppression screens.
Wicking tests were run using horizontal screens and heaters to determine the capability
of wicking screens in preventing screen drying.

MAJOR RESULTS. -

1. The LO_2 design for the S-IVC (Figure 1) consisted of a cylinder cone arrangement
   over the outlet. The LH_2 tank reverse bulkhead design consisted of a torus extend-
   ing 60° on either side of the sidewall mounted outlet.

2. The LOX tanker design employed a reservoir over the outlet for maintaining liquid
   outflow when a disturbance caused liquid to be reoriented off the tank walls.

3. Scale model spilling tests were successfully correlated with the INGASP computer
   model predictions of vapor ingestion and spilling during capillary device startup
   (Figure 2).

4. Residuals tests were successfully correlated with the Dregs 2 computer model
   prediction of capillary device draining (Figure 3).

5. Outflow tests run with screen baffles indicated that interface shape during draining
   and screen flow pressure drops can be used to predict screeen pullthrough suppres-
   sion performance.

COMMENTS. - See Symons, 1974 for more extensive wicking data.
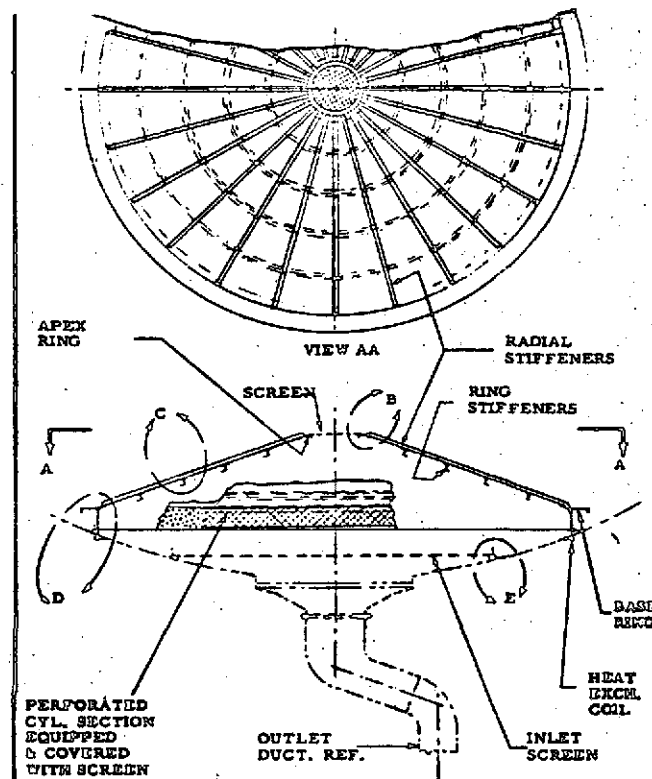
Figure 1. Oxidizer Reservoir Structural Arrangement
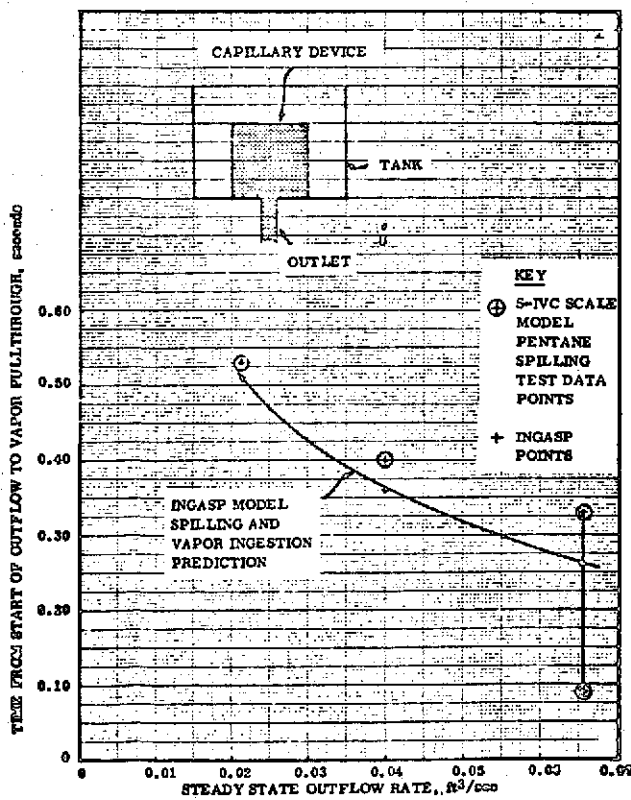
Figure 2. S-IVC Scale Model Spilling Tests
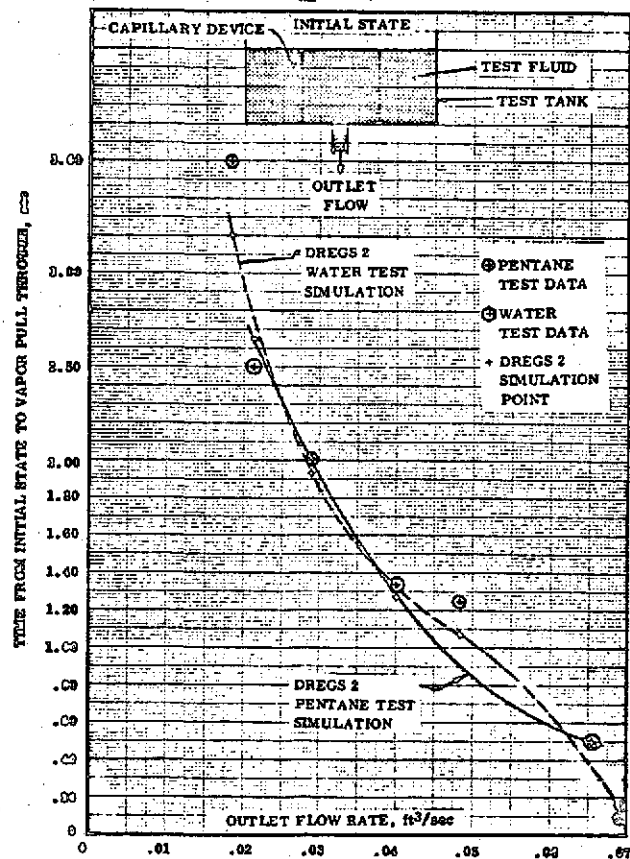
Figure 3. S-IVC Scale Model Residual Test Correlation

LOW GRAVITY PROPELLANT CONTROL USING CAPILLARY
DEVICES IN LARGE SCALE CRYOGENIC VEHICLES DESIGN
HANDBOOK, Blatt, M. H., et al, GD/C, GDC-DDB70-006,
NAS8-21465, August 1970

OBJECTIVE. - Provide fluid, thermal and structural design information for cryogenic
capillary propellant control device design.

PERTINENT WORK PERFORMED. - The work was divided into three areas; fluid,
thermal and structural design. Short descriptions of the design requirements were
followed by a flow chart for conducting the analyses and design in each area.

The flow chart for fluid analysis indicated that initially a preliminary capillary device
configuration should be determined for the mission conditions based on retention capa-
bility, volumetric requirements, refilling and spilling considerations and maintaining
minimum surface to volume ratio. The configuration should be revised and finalized
based on additional analysis of wicking, pullthrough suppression, deflecting ingested
vapor, sloshing, settling, venting pressurization, spilling, refilling and draining.

The fluid analysis chapter detailed methods of analyzing retention, screen flow, wick-
ing, settling and sloshing, spilling and vapor ingestion, refilling, tank filling, residu-
als, entrained vapor impingement, venting, pressure collapse, and bubble dynamics.

The thermal analysis chapter detailed methods of analyzing active cooling of a capil-
lary device with a thermodynamic vent system. After determining incident heating,
vent flow rates, and heat balance on the tank and capillary device, a detailed definition
of the cooling configuration should be determined based on mixing and cooling flow data
over the full range of fluid conditions expected. A complete thermal analysis should
then be done, using a thermal analyzer program, or the fin equations presented, in
order to define the cooling tube locations, attachments, spacing, throttling pressures,
mixing flow and mixer location and vent flow path. Mixing, heat transfer, and ther-
mal control were dealt with in separate sections. Mixing, heat transfer, and vent
system sizing equations were presented.

Structural and manufacturing considerations were discussed in the final chapter.
Based on the vehicle tank geometry and hydrodynamic analyses, an overall profile and
structural arrangement for the device should be determined. This should be used to
examine external and internal loading conditions in order to establish materials re-
quirements, gauges and sizes of supporting members, screen attachment methods,
heat exchanger tube attachment methods and stiffener requirements. Specific sections
dealt with loads, materials, screen attachments, heat exchanger attachments, con-
figurations for minimum weight, and screen clogging.

COMMENTS. - The report contains useful information related to cryogenic start bas-
kets cooled with thermodynamic vent system flow. For start tank system data, see
Burge and Blackmon, 1973. For screen liner vent/acquisition system data, see
Paynter and Page, Vol. II, 1973.

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A SURVEY OF CURRENT DEVELOPMENTS IN SURFACE
TENSION DEVICES FOR PROPELLANT ACQUISITION
De Brock, S. C., et al, LMSC; AIAA Paper No. 70-685,
June 1970

OBJECTIVE. - Survey current developments in capillary propellant acquisition devices.

PERTINENT WORK PERFORMED. - Analysis techniques, performance test methods,
materials compatibility structural test methods, fabrication, handling, acceptance
testing,and flight experience with capillary propellant acquisition devices were described.

Capillary devices were compared to other methods of expulsion. Capillary devices
have the principal attributes of passiveness and consequent high reliability for long
life missions. Advantages and disadvantages of other methods are presented in Table 1.
Capillary acquisition device designs were described for; partial retention devices that
rely upon settling for refill (Agena, Apollo, Mariner 71), and total communication
approaches such as tank liners or channels (X-15 Flight Research Vehicle, 62 inch
hydrazine gallery design and Viking).

Capillary system flight experience is summarized in Table 2. Characteristics of
each of these flight proven systems were described. Fluids transferred by these
systems ranged from Cesium to JP5.

Methods of analyzing capillary acquisition devices were described with a plethora of
references cited. Areas considered were propellant surface shape, stability, liquid
reorientation, start transients, and surface drainage dips. Additional work was
recommended in the area of liquid reorientation and startup transients.

Performance testing was described, particulary related to model testing (See De Brock
1973). Descriptions were given of mission events to be evaluated, dominant variables
and test methods. Use of these methods on Agena was described related to static and
dynamic retention, transient propellant withdrawal, restart and geysering and refill
during fluid reorientation.

Materials compatibility testing being conducted at JPL was described. Surface
tension tests to determine the time dependence of surface tension with several
propellant/material combinations were about to be conducted for screen materials.

Resistance spot welding techniques were described for fabricating screen devices.
Subassembly procedures for capillary device installation and removal in the tank were
described. Acceptance testing commonly consists of bubble testing.

COMMENTS. - The LEM and Transtage propellant restart devices cited in Table
2 have not actually been flight tested since propellant is settled with ACS engines prior
to engine restart.

Table 1. Positive Expulsion System Comparison

EXPULSION SYSTEM	STRONG POINTS	PROBLEM AREAS
Pistons	Positive displacement; variable initial ullage gas volumes	Heavy; leakage; jamming due to cocking or corrosion; limited to cylindrical tanks
Bladders	Much development and flight experience; adaptable to most tank geometries and initial gas ullage volume	Long term compatibility; gas permeation; poor expulsion efficiency; folding geometry conducive to pinhole leaks
Metallic Bellows	Good compatibility; predictable performance adaptable to varying tank geometries and initial ullage volumes	High weight; cocking during expulsion
Elastomeric Diaphragm	Good expulsion efficiency; trouble free and repeatable diaphragm geometry during expulsion	Poor wear characteristics during prolonged propellant slosh; poor long life compatibility; limited to spherical tank geometry with significant initial ullage volume
Metallic Diaphragm	Good compatibility; not sensitive to propellant slosh	Limited to spherical tank geometry with significant initial ullage volume; high ΔP required for expulsion
Rolling Diaphragm	Good compatibility; not dependent on initial ullage volume	High ΔP required for expulsion; limited to cylindrical tank geometry

Table 2. Summary of Flight Experience

FLIGHT APPLICATION	BASIC FUNCTION	NO. OF FLIGHTS
Current Agena	Propellant retention and propellant supply during low-g restarts	>120
Apollo Service Module	Propellant retention and gas phase flow blockage during propellant settling	11
Apollo Lunar Excursion Module	Propellant retention in feed line	6
Transtage	Gas phase flow blockage during propellant settling	>20
ATS Cesium Ion Propulsion Subsystem	Vapor phase propellant feed	3
MQM - 74A Drone	Gas phase flow blockage	322
Firebee II Drone	Gas phase flow blockage	9

EXPERIMENTAL INVESTIGATION OF CAPILLARY PROPELLANT
CONTROL DEVICES FOR LOW GRAVITY ENVIRONMENTS
Paynter, H.L., MMC, MCR-69-585, (Vol. I and Vol. II),
Contract No. NAS8-21259, June 1970

OBJECTIVE. - Experimentally investigate; the liquid/gas interfacial stability of
perforated plate under an acceleration acting both normal and parallel to the surface,
passive schemes for preventing the passage of settled propellants, and liquid filling
of capillary annuli.

PERTINENT WORK PERFORMED. - All work was done in the Martin 2.1 second drop
tower. Stability criteria tests for acceleration perpendicular to square weave screen
and perforated plate were described thoroughly in Barksdale and Paynter 1968.
Damping tests, similar to stability tests, were run with liquid initially below the level
of the barrier. An acceleration was applied normal to the surface of the barrier to
reorient the (flat surfaced) fluid to the opposite end of the transparent flat bottomed
cylindrical tank. Barriers evaluated were; single and double perforated plate, single
and double square weave screen, multi-tube and single tube configurations, and single
layer dutch-twill cloth.

The hydrostatic stability of dutch-twill and square weave screen and perforated
plates were evaluated for accelerations imposed parallel to the plane of the barrier
material. Liquid initially was 1/4" or less above the barriers. A dimensionless
number, ϕ, representing the ratio of acceleration to surface forces was used to
delineate between stable and unstable interface behavior. $\phi = a_L \, hr/\beta$, where a_L =
lateral acceleration, h = lateral distance (tank diameter), r is the pore radius and
β is the dynamic surface tension. Twenty one drop tests were made using simple
cylindrical and spherical glass specimens, with a concentric screen liner to provide
a liquid flow annulus, for evaluating capillary refilling of annuli. Filling theory was
presented for computing the capillary fill rate based upon surface tension and friction
forces.

MAJOR RESULTS. -

1. Performance of porous barriers in damping settling flow was characterized into
   six flow regimes. (Table 1). Results shown in Figure 1, as a function of barrier
   Weber number, indicate that dutch twill screens, because of their small pore size,
   resist the passage of settling flow. In Figure 1, ξ is the ratio of open to closed area.

2. For interface stability with accelerations parallel to the porous barrier, values of
   ϕ were found to be; $\phi \sim 1.1$ for dutch twilled screen and $0.85 < \phi < 0.95$ for square
   weave screen. For perforated plate, $2.1 < \phi < 2.5$ for $9.5 \leq \xi \leq 22.7\%$ and $1.2 <
   \phi < 1.7$ for $\xi = 36.2\%$,

3. For capillary filling of annuli comparison of data and predictions is shown in
   Figure 2. General conclusions were that perforated plate or square weave screen
   will be required to prevent wicking from impeding annulus filling.

Table 1. Damping Flow Regimes

A No liquid passes through the barrier;

B Some liquid (relatively little) passes during wetting of the
barrier by liquid settling along the wall of the cylindrical
specimen;

C The dome of the liquid column either penetrates the barrier,
resulting in a sessile globule, or recedes completely;

D The central liquid mass penetrates the barrier as one or
two columns that pinch off and stay above the barrier, but
no additional liquid passes;

E Similar to D, but the columns are not completely pinched off;

F A considerable amount of liquid passes through most of the
barrier surface, and there is a number of columns (streamers);

G A massive amount of liquid passes through the barrier with
no apparent damping.

Figure 1. Damping Performance of
Selected Barriers

Figure 2. Annulus Fill Time vs Liquid-
to-Container Volume Ratio

11-35

PROPELLANT POSITION CONTROL BY CAPILLARY
BARRIERS DURING SPACECRAFT ROTATIONAL MANEUVERS
Gluck, D.F., NAR, AIAA 5th Joint Propellant Specialists
Conference, March 1970

OBJECTIVE. - Analytically and experimentally determine a critical Weber number
for incipient gas passage through a rotating barrier during rotational maneuvers.

PERTINENT WORK PERFORMED. - A simple capillary barrier (Figure 1) for
engine restart was analyzed to determine the effect of rotational maneuvers on
liquid and vapor flow through the capillary barrier. Flow was taken to be incom-
pressible, inviscid and irrotational. The cylindrical tank was filled to a height h
just above the capillary barrier. A short duration, high torque angular impulse was
applied instantaneously generating the rotation. For centerline clockwise motion
the flow field tended to cause gas passage at the hole on the extreme right of the
barrier. A model of this pore is shown in Figure 2. The critical case occurs when
the interface is pulled just to the hemispherical shape. An equation was formulated
relating the conditions at incipient gas passage through the barrier to the tank
geometry and location of the axis of rotation. The barrier hole size does not enter
into the relationship. The theory was limited by the assumption that the openness
of the screen is one.

Experimental data was obtained in order to determine the influence of the critical
Weber number on the openness ratio Op. Tests were conducted in 4.75" and 5.0" I.D.
plexiglas model cylindrical tanks with hemispherical ends. Carbon tetrachloride was
used as the test fluid. Twenty two useful tests were obtained from the KC-135 testing.

MAJOR RESULTS. -

1. Experimental data is shown in Figure 3 (see Table 1 for nomenclature) to delineate
   between stable and unstable barrier behavior as a function of actual Weber number,
   openeness ratio and theoretical critical Weber number. Critical Weber number
   increases significantly with increasing openness ratio.

COMMENTS. - Results of this paper should be compared to lateral and normal
stability and retention capability to formulate critical design criteria for barrier sizing
for typical mission requirements.

Table 1. Nomenclature

a = tank radius
d = diameter of hole or perforation in capillary barrier
$F(t)$ = function of time in Bernoulli equation
g = acceleration or gravity field
h = height of the barrier above the tank bottom, where volume below barrier is taken as an equivalent right circular cylinder
J_1 = Bessel function of first order and first kind
l = normal distance from center of rotation to barrier
O_p = ratio of hole area to total barrier area
P = pressure; P_G = gas pressure
q = velocity vector
r = a cylindrical coordinate in inertial frame instantaneously coinciding with tank radial coordinate
R = radius of curvature
s = average height of liquid above capillary barrier
t = time
U = velocity in x direction
V = volume of spherical segment
W = velocity in Z direction
We_c = critical Weber number, value of Weber number at incipient gas passage through barrier
W_R = velocity of liquid through barrier hole relative to tank velocity
$\langle W \rangle_R$ = average value of W_R during growth of interface to maximum size

W_t = tank velocity in Z direction
x = coordinate in inertial framework
X = height of spherical segment
Z = coordinate in inertial frame instantaneously coinciding with the tank axis, taken as positive in the downward direction
η = coefficient of bubble pressure term
θ = rotation rate about axis perpendicular to tank longitudinal axis
ν = kinematic viscosity
ξ_n = roots of J_1 (arg) $= 0$
ρ = liquid density
σ = liquid surface tension
φ = angular coordinate in inertial framework instantaneously coinciding with tank coordinate
Φ = velocity potential
Φ_F = final velocity potential for case of O_p approaching 1
Φ_0 = initial velocity potential for case of O_p approaching 1
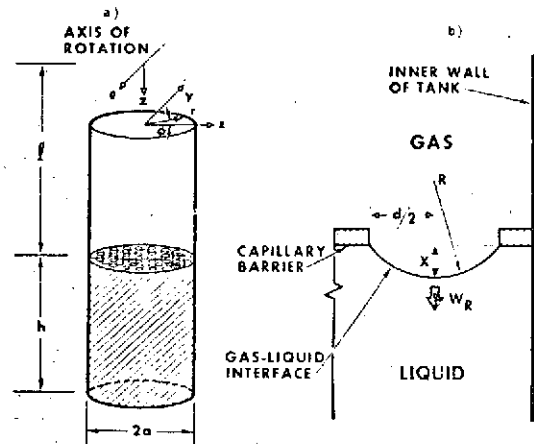
Figure 1. Model for Theoretical Development, a) Total Model, b) Interface Growth at Most Vulnerable Hole
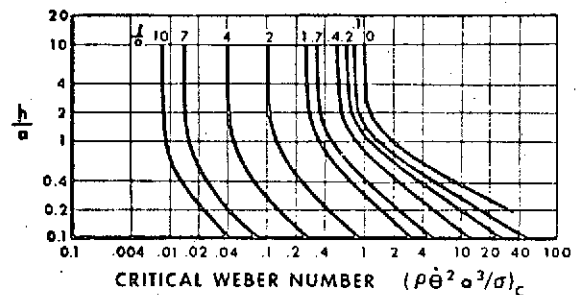
Figure 2. Critical Weber number as a Function of Geometry and Position of Axis of Rotation
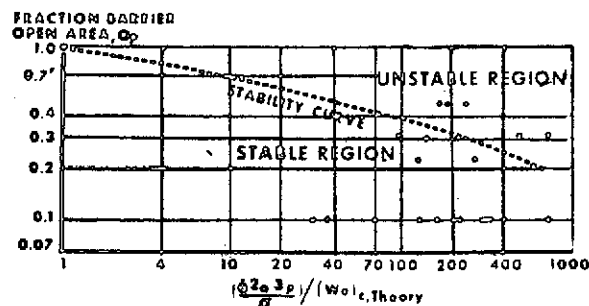
Figure 3. Normalized Capillary Barrier Stability Results

ADVANCED PROPELLANT MANAGEMENT SYSTEM FOR SPACE-
CRAFT PROPULSION SYSTEMS
Balzer, D.L., et al, MMC, MCR-69-436, NAS9-8939,
September 1969

OBJECTIVE. - Develop capillary propellant management system designs for the oxidizer and fuel tanks of an Apollo spacecraft propulsion system.

PERTINENT WORK PERFORMED. - For design groundrules and configuration requirements, see Section 10.0, Barksdale, 1969. Identical designs were selected for both oxidizer and fuel tanks, although requirements for the oxidizer tank were more stringent. Designs were developed both for retrofit within the baseline tankage (Figure 1) and for a no-hardware limitation configuration (Figure 2). Device geometry was influenced mainly by containing sufficient fluid to perform 500 restarts independent of the system thrust profile. Screen sizing was primarily based on the acceleration environment. Analyses were conducted to support the design effort. These analyses considered screen static retention capability, hydrostatic stability at the screen, damping of liquid motion by capillary barriers, reorientation, refilling, and draining. The Marker and Cell technique was used to compute initial fluid motion during both reorientation and annulus draining. A plexiglass model of the existing Apollo spacecraft propulsion system, approximately one-fifth scale, was used with a model of the capillary device. Sixty-eight tests were conducted. Five drop tests were run demonstrating the retention capability of the coverplate screen assembly under a lateral acceleration environment. Seventeen resettle tests were conducted. These tests dropped liquid on the capillary device from a screened compartment that stabilized the liquid to be settled. The pressure supported liquid was released when the compartment vent valve was opened. Low gravity interface shapes were analytically determined for the liquid vapor interface in both compartments of the propellant trap. The configuration analyzed is shown in Figure 3. A series of 19 drop tests were run using 1/5 and 1/12 scale model tanks.

MAJOR RESULTS. -

1. No difficulties were experienced in filling the liner completely if the screen was dry before introduction of the fluid and the fill rate exceeded the screen wicking rate.

2. Liquid settling and capillary device refill tests demonstrated successful capillary device refilling during outflow.

3. Interface configurations found from drop tests demonstrated that sufficient liquid would contact the screens to accomplish low gravity restart.

COMMENTS. - The report does not discuss the correlation, if any, between the settling and interface configuration analyses and test.

Note: All materials 300 series stainless except as noted

.020 Wall
.020
Section E
No Scale
.375 Typ

Connecting Joint for Frame

Titanium Double Perforated Plate (.020 Dia)

Alum

.020
.015
.020
Brackets (4 Plcs)

Dutch Twill Screen (30 x 250 Mesh) with Perforated Sheet (.020 Dia) Backup (Stainless Steel)
Section F
No Scale

Dutch Twill Screen (30 x 250 Mesh) with Perforated Sheet (.020 Dia) Backup (Stainless Steel)

Tension Strap (13 Plcs)

Pleated Screen Liner

Screen .015
Perforated Plate L .31 x .35 x .015 Each Side

.015
.020
Section C-C

Pleated Screen

Section D
No Scale

Sump Assembly

Section B
No Scale

Figure 1. Retrofit Design

Perforated Plate
Section A-A

Dutch Twill Screen (30 x 250 Mesh) with Perforated Sheet (.020 Dia) Backup (Stainless Steel)
Double Perforated Plate (.020 Dia)

Double Perforated Plate (.020 Dia)

Dutch Twill Screen (30 x 250 Mesh) with Perforated Sheet (.020 Dia) Backup (Stainless Steel)

Pleated Stainless Steel Dutch Twill Screen

Figure 2. No Hardware Limitation Design

Tank Acceleration (g)

Gas   Gas

h_1

Liquid   Liquid

r_1
r_2
r_3

z

r

Figure 3. Configuration for Computer Analysis

DESIGN, FABRICATION AND TESTING OF SUBSCALE
PROPELLANT TANKS WITH CAPILLARY TRAPS
Barksdale, T.R., Paynter, H.L., MMC,
MCR-68-11, NAS8-20837, March 1968

OBJECTIVE. - Experimentally determine the Bond number stability criteria for
square weave screens and perforated plates.

PERTINENT WORK PERFORMED. - Tests were conducted over an acceleration range
of 0.0013 to 0.055 g in Martin's 2.1 second drop tower facility. The acceleration
was applied normal to the flat plates and screens tending to reorient the liquid from
beneath the barriers to the opposite end of the $5\frac{1}{2}$ " O.D transparent flat bottomed
cylinders. Tests were conducted with 39 perforated plates and 13 square weave
screens (Table 1, Figure 1). Two specimens were tested in each drop with the liquid
level in the tanks sufficient to cover the barrier material and assure wetting prior to
applying the destabilizing acceleration. Methanol, carbon tetrachloride and Freon
TF were used as the test fluids. A literature search of hydrostatic stability was
conducted and was presented in the Appendix of the report.

MAJOR RESULTS. -

1. The theoretical critical Bond number $(\rho a R^2/\sigma)$ of 0.842 where R is the radius of the
   hole and a is the dimensionless acceleration, delineating between stable and unstable
   liquid vapor interfaces at a perforated plate was compared to experimental data
   (Figure 2). Results agree fairly well between data and predictions.

2. The critical Bond number for square weave screen was experimentally found to be
   0.45 where R is half the screen opening (Figure 3).
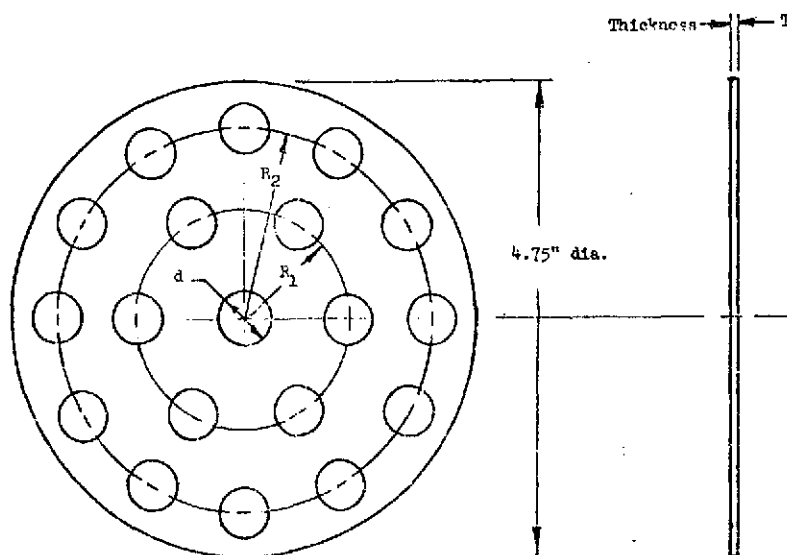
Figure 1. Typical Hole Layout Pattern for Plates With Constant Hole Size (See Table 1).
N = Number of Holes per Hole Circle.

Perforated plate barrier specifications
see Figure 1 for nomenclature

Plate No.	Matl.	R₁ in.	N₁	R₂ in.	N₂	R₃ in.	N₃	d in.	T in.
1	S.S.	1.38	8					.688	.020
2	S.S.	0.80	8	1.37	8	2.05	8	.344	.020
3	S.S.	1.64	8					.812	.020
4	S.S.	0.81	8	1.65	8			.438	.020
5	S.S.	1.93	8					1.062	.020
6	S.S.	1.05	8	2.11	8			.531	.020
7	Al	Contains three pore sizes with largest pore in center. Five plates with same hole layout, but different thickness, 0.016, 0.032, 0.087, 0.125, and 0.190 in.						.344 / .313 / .281	
8	Al	Contains three pore sizes with smallest hole in center. Same thickness as in plate 7						.281 / .313 / .344	
9	Al	0.56	6	1.12	12	1.70	18	.281	.087
10	Al	0.88	6	1.77	12			.437	.087
11	Al	1.44	6					.719	.087
12	Al	Three pore sizes with larger pore in center						.500 / .406 / .344	.087
13	Al	1.00	6	2.00	12			.500	.087
14	Al	Three pore sizes with larger pore in center						.681 / .625 / .562	.087
15	Al	1.06	6	2.12	12			.531	.087
16	Al	Three pore sizes with larger pores on inner hole circle (1.75 dia.) Pores on outer hole circle (3.75" dia.) are alternately .0612 and 0.750						.875 / .812 / .750	.087
17	Al	1.35	6					.625	.087
18	Al	1.87	6					.937	.087
19	Al	0.62	6	1.25	12	1.88	18	.313	.087
20	Al	0.86	6	1.75	12			.375	.087
21	Al	0.81	6	1.62	12			.406	.087
22	Al	1.19	6	1.90	6			.594	.087
23	Al	1.12	6	2.00	12			.562	.087
24	Al	0.79	6	1.57	12	2.06	18	.344	.087
25	Al	0.94	6	1.88	12			.469	.087
26	Al	1.56	6					.781	.087
27	Al	1.74	6					.969	.087
28	Al	1.31	6					.656	.087
29	Al	1.62	6					.812	.087
30	Al	1.55	5					.937	.087
31	Al	1.37	6					.687	.087
32	Al	1.80	6					.906	.087
33	Al							3.406	.087
34	Al							3.594	.087
35	Al							2.156	.087
36	Al							2.344	.087
37	Al							2.593	.087
38	Al							2.781	.087
39	Al							4.562	.120

Material Abbreviations: S.S. = stainless steel
Al = aluminum
Br = brass

B. Square Weave Screen Barrier Specifications

Screen No.	Material	Mesh	Wire dia. in.	Open Width in.
S-1	Br.	1	0.192	.808
S-2	S.S.	5/8/2	0.120/.080	.505/.420
S-3	S.S.	2½/2½/2	.080/.080/.105	.364/.320/.395
S-4	S.S.	2½	0.092	.352
S-5	S.S.	1	0.162	.838
S-6	S.S.	2	0.080	.420
S-7	S.S.	2	0.092	.408
S-8	S.S.	1	0.120	.880
S-9	S.S.	5	0.041	.159
S-10	S.S.	3½	0.080	.206
S-11	S.S.	3	0.054	.279
S-12	S.S.	2½	0.080	.320
S-13	S.S.	5/8"	0.080	.505

Table 1. Foraminous Barrier Specification
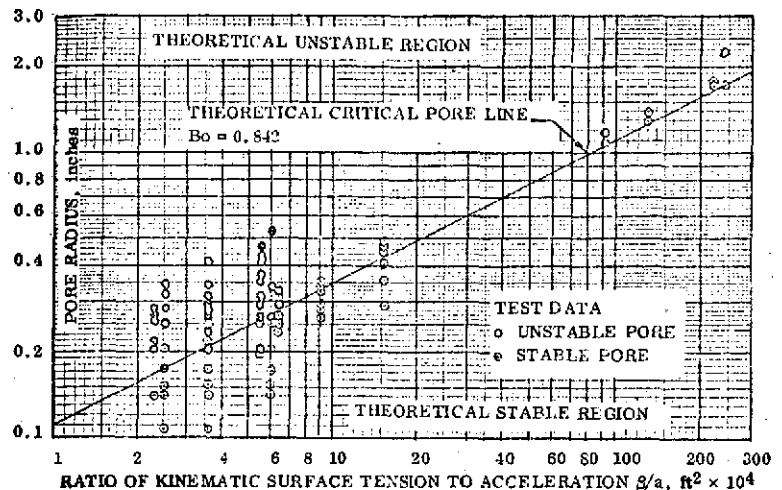
Figure 2. Stability Characteristics for Perforated Plate Barriers
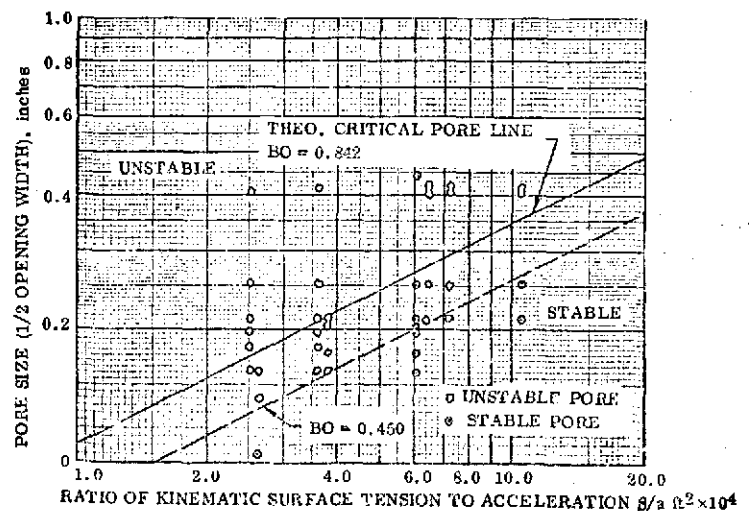
Figure 3. Stability Characteristics of Square Weave Screen Barriers

12.0 POSITIVE EXPULSION

Covering bladders, bellows, diaphragms and pistons, with expanding or contracting surfaces to control orientation and/or to allow liquid expulsion at low-g.

ELASTOMERS FOR LIQUID ROCKET PROPELLANT CONTAINMENT
Martin, J.W., Green, H.E., TRW, AFML-TR-71-59 (Part II),
F33(615)-71-C-1233, October 1973

OBJECTIVE. - To evaluate new elastomeric compounds for use as seal and positive expulsion diaphragm materials with hydrazine, dinitrogen tetroxide (N_2O_4), aircraft hydraulic fluids, and fluorinated oxidizers.

PERTINENT WORK PERFORMED. - Elastomers and applications evaluated included AF-E-332 for hydrazine expulsion, AF-E-411 for hydrazine seals, AF-E-124D for hydrazine and N_2O_4 expulsion, carboxynitroso rubber (CNR)/HYSTL composites for N_2O_4 expulsion, and two TRW-developed elastomers for hydraulic fluids. A new bladder fabrication technique was developed. A pressurized (1000 psi during forming) silicone rubber bag was formed to serve as the internal mandrel and a conventional two-piece female mold was used to form the outside surface. A 10.5-in. Mariner mold was used to produce bladders that exhibited uniformity and properites similar to those slab-molded under much higher pressure (Table 1). Three 4-in. AF-E-332 diaphragms were used to expel hydrazine 332 times at room temperature and 100 times at 160F, and alcohol 100 times at -40F, respectively, with no degradation. A 10.5-in. bladder made from the same material successfully expelled hydrazine with an expulsion efficiency of 99 percent. Long term storability test with hydrazine at 140F indicated that the -332 material is highly compatible with the propellant (Table 2). A 4-in. bladder fabricated from AF-E-124D was unaffected by 500 room-temperature (RT) expulsion cycles with water and an additional 941 RT cycles with N_2O_4. This elastomer is characterized by good strength but susceptibility to creep after cure, high cure shrinkage, and better resistance to oxidation than any other elastomer (Table 3).

MAJOR RESULTS. -

1. A new, low-cost bladder fabrication technique was developed.

2. A new material, AF-E-332, apparently meets all of the present requirements for a hydrazine bladder or diaphragm elastomer. It is readily processable, not degraded by hydrazine up to 160F, has no effect on fluid decomposition rate, and exhibits high cycle lifetime.

3. CNR and AF-E-124D, while not developed to the extent of AF-E-332, show excellent promise, particularly for use with N_2O_4.

Table 1. Hydrazine Permeability of 332-6 Bladder

Specimen	Thickness, Inches	ΔP	Test Duration Hours	Rate, mg/cm^2-hr
Slab Molding	0.050	1 Atm	312	0.018
Bladder	0.080	1 Atm	720	0.0055

Table 2. Pressure Rise Tests of AF-E-332 Bladders

(Hydrazine Storage at AFRPL)

Bladder Tank No.	One Month, psi	Three Months, psi	Five Months psi	Fifteen Months, psi
S/N 008	9	15	15	25
S/N 010	8	14	18	18
Corresponding Tank Temperature °F	137	140	140	144

Table 3. Retention of AF-E-124D Mechanical Properties
After 8 Days in N_2O_4

Storage Temperature	Tensile Retained	Elongation Retained	Shore A Hardness
75°F	96%	100%	±0
120°F	95%	95%	-1
160°F	92%	96%	-3
200°F	51%	180%	-18

SURVEY OF MATERIALS FOR HYDRAZINE PROPULSION SYSTEMS
IN MULTICYCLE EXTENDED LIFE APPLICATIONS
Coulbert, C.D., Yankura, G., JPL, NASA TM 33-561,
September 1972

OBJECTIVE. - The objective of this report was to summarize and assess the existing
information and data on materials compatibility with hydrazine monopropellant as
applied to the requirements of Space Shuttle vehicle auxiliary propulsion systems.

PERTINENT WORK PERFORMED. - Materials were evaluated for application over a
10-year/100- mission operational lifetime with minimum refurbishment. The tempera-
ture range of interest spans the normal hydrazine liquid range (2 to 110C). The two
principal phenomena of concern in this study are (1) effect of materials on hydrazine
decomposition, and (2) effect of hydrazine on material properties. However, for the
shuttle mission, change in the hydrazine composition over a several year period may
not be a problem, since the system will be used, drained, and refilled many times
over the 10-year period. Of greater concern are the bladders, tanks, and seals
which must survive the full vehicle life cycle. The three major types of metallic
materials investigated are alloys of aluminum, titanium, and stainless steels. Non-
metallic materials, for use as diaphragms, valve seats, or seals, were investigated
with the best results being obtained with ethylene propylene rubbers (EPR) and ethylene
propylene terpolymer (EPT) compounds.

The appendices of the report contain reproductions from a report by Martin on material
compatibility with hydrazine, a report by Rocketdyne on hydrazine decomposition studies,
a report by Pressure Systems, Inc., on EPT-10 properties as a function of hydrazine
immersion time, and a summary of JPL elastomer physical property data.

MAJOR RESULTS. -

1. A number of commercial alloys of aluminum, titanium and stainless steel can be
   used in hydrazine systems for long-term storage.

2. EPR and EPT elastomeric compounds are the most promising for use with hydrazine.
   To date they have been judged satisfactory for one to two year mission applications
   with minimum cycling.

COMMENTS. - See the summary of the material study by Martin and Green (1973)
for additional information on elastomeric materials.

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STUDY OF LOW-GRAVITY PROPELLANT TRANSFER - FINAL REPORT
Stark, J.A., GD/C, GDC-DDB72-002, NAS8-26236, June 1972

OBJECTIVE. - To perform an analytical assessment of potential methods for replenishing the auxiliary propulsion, fuel cell, and life support cryogens which may be aboard an orbiting space station.

PERTINENT WORK PERFORMED. - For subcritical liquid transfer various types of expulsion techniques were analyzed and four were selected for detailed evaluation: surface tension, metallic bellows, metallic diaphragm, and paddle vortex systems. Detailed definitions and parametric weight data were developed for various configurations of each expulsion technique. Heat transfer, pressurization, fluid residual, and chill down analyses were made. For the bellows-type system, each configuration was required to contain a total liquid volume of 42.5 ft^3 and be capable of expulsion into a receiver tank at 100 psia. The bellows were assumed to be fabricated from 0.010-inch thick CRES 347, and be of the nested-hydroform type. High pressure helium was the assumed pressurant gas, and liquid hydrogen the fluid to be transferred.

Various bellows configurations were selected to determine the overall effects on system weight of bellows and pressurant bottle design and packaging, and bellows length to diameter (L/D) ratio. A configuration with a spherical, titanium helium bottle located inside the tank envelope, and a bellows L/D of 1.5 was found to result in minimum weight (Figure 1). For this configuration, parametric weight data were then generated over the range of propellant volumes from 4.7 to 1020 ft^3 and tank pressures from 50 to 500 psi. Weights of the total supply system (including LH$_2$) as a function of mass transferred are shown in Figure 2 for the various transfer techniques mentioned above, plus modular (tank exchange) and high pressure (supercritical) transfer methods.

MAJOR RESULTS. -

1. Compared with the other subcritical systems, the metallic bellows was found to have the highest weight and unit cost, and lowest potential reliability.

2. While possessing a high expulsion efficiency, $\left| \text{(fluid loaded)} - \text{(fluid remaining)} \right| /$ (fluid loaded), the bellows system has a relatively low volumetric efficiency, $\left| \text{(total tank volume)} - \text{(unusable volume)} \right| / \text{(total tank volume)}$.

3. It was recommended that the metallic bellows system not be a primary development target for this particular resupply application.

Figure 1. Bellows System, Configuration E

Figure 2. H$_2$ Supply System Weights Including Fluid (Wet)

INVESTIGATION OF THE FEASIBILITY OF DEVELOPING LOW
PERMEABILITY POLYMERIC FILM
Hoggatt, J. T., Boeing Co., NASA CR-120892, NAS 3-13326,
December 1971

OBJECTIVE. - To determine the feasibility of reducing the gas permeability rate of
Mylar and Kapton films without drastically affecting their flexibility at cryogenic
temperatures.

PERTIENT WORK PERFORMED. - Both 1/4 and 1/2-mil Mylar and Kapton films
were evaluation in this program. Each lot was characterized, the data serving as a
basis for comparison in assessing the effects of metallizing and laminating on perme-
ability and flexibility. Helium permeability at 21, -195, and -252C and liquid hydrogen
permeability at -252C were measured with the materials in both unstressed and stressed
(20 percent of ultimate) conditions. Stressing the films resulted in 1 to 3 orders of
magnitude increase in helium permeability, but a decrease in LH_2 permeability.
One side of each type of film was vacuum or sputter-metallized with aluminum or
gold to a thickness of 5000 or 10,000 angstroms. Vacuum metallizing did not result
in any reduction in permeability, while sputtered coatings reduce helium permeability
by approximately two orders of magnitude. Metallizing was found to reduce the
flex life of the film. The goldized Kapton films were formed into a two-ply laminate
by stacking the sheets with the two metallized surfaces in contact with one another,
and then applying heat (300C) and pressure (84.4 kg/cm^2) for five minutes to diffusion
bond the two surfaces together. Diffusion bonded samples were subjected to the
same types of permeability and flex testing.

MAJOR RESULTS. -

1. Diffusion bonding of sputtered coatings reduces the film helium permeability by
   at least four orders of magnitude over the plain film and appears independent of the
   thickness of the metallized coating (above 3000 angstroms).

2. Metallizing the films reduces the cryogenic flexibility slightly. The diffusion
   bonding process, however, did not appear to result in further flexibility reductions.

3. The laminate concept is applicable as a barrier ply for polymeric expulsion devices,
   cryogenic insulation systems, and as a space-stable bagging material where a
   combination of low permeability and flexibility is important.

4. Bladder permeability rates are shown in Table 1.

Concept	Material	Film Stress 0%	20%	Film Thickness mils	Coating Material	Thickness $\mathring{A} \times 10^{-3}$	Total Specimen Thickness mils	Specific Permeability of Helium (cc-mm/cm^{2}sec cm Hg)
Plain Film	Mylar	X		.25	-	-	.25	11.4×10^{-9}
			X	.25	-	-	.25	54.8×10^{-9}
		X		.50	-	-	.50	0.24×10^{-9}
			X	.50	-	-	.50	16.8×10^{-9}
	Kapton	X		.25	-	-	.25	3.73×10^{-9}
			X	.25	-	-	.25	95.0×10^{-9}
		X		.50	-	-	.50	0.40×10^{-9}
			X	.50	-	-	.50	1.73×10^{-9}
		X		1.00	-	-	1.00	2.49×10^{-9}
Metallized (Sputtered One Side Only)	Kapton	X		.25	Gold	10	.25	0.29×10^{-11}
		X		.50	"	5	.50	9.0×10^{-11}
		X		"	"	10	"	7.2×10^{-11}
		X		"	Aluminum	10	"	3.55×10^{-11}
			X	"	"	"	"	5.72×10^{-11}
	Mylar	X		"	"	"	"	7.13×10^{-11}
			X	"	"	"	"	20.3×10^{-11}
	Kapton	X		.25	"	5	.25	2.1×10^{-11}
			X	.25	Aluminum	5	.25	2.95×10^{-11}
Laminated Film (Sputtered Coating- Diffusion bonded)	Kapton	X		.25	Gold	5	.50	3.59×10^{-13}
			X	"	"	5	"	426.0×10^{-13}
		X		"	"	10	"	1.68×10^{-13}
			X	"	"	10	"	139.0×10^{-13}
		X		.50	"	5	1.00	5.36×10^{-13}
			X	"	"	5	"	3.61×10^{-13}
		X		"	"	10	"	0.73×10^{-13}
			X	.50	Gold	10	1.00	2.65×10^{-13}
Laminated Film (Vacuum Deposited Coating-Diffusion Bending)	Kapton	X		.25	Gold	10	.50	7.7×10^{-11}
			X	.25	"	10	.50	9.7×10^{-11}
		X		.50	"	10	1.00	7.15×10^{-11}
			X	.50	"	10	1.00	16.8×10^{-11}

Table 1. Average Specific Permeability Rates at +70° F

EVALUATION OF METALLIC POSITIVE EXPULSION BELLOWS
OPERATING PARAMETERS WITH CRYOGENIC PROPELLANTS
Lange, R.L., Hughes, J. T., Bell Aerospace, NASA CR-72979,
NAS3-13327, July 1971.

OBJECTIVE. - To determine the performance of an existing, seamless bellows config-
uration at cryogenic temperatures, and to revise existing design computer programs
to incorporate characteristics associated with cryogenic temperatures.

PERTINENT WORK PERFORMED. - The bellows core design was identical to that
developed for MMH and N_2O_4 expulsion on the Minuteman vehicle. A 7 mil seamless
CRES 347 tube, 12.5 in. in diameter, was expanded into bellows forming dies by
internal pressurization and then each convolution was compressed between two dies
forming the root and crest bend radii and sidewall shape. A total of 22 bellows cores
were manufactured in this manner by DK Aerospace division of MSL Industries, Inc.
These were subsequently tungsten-inert-gas (TIG) welded to end plate closure assem-
blies by Bell. These assemblies were subjected to an extensive series of tests at
cryogenic temperatures, which were identical to the standard Minuteman series
performed at room temperature, to expose performance variations resulting solely
from the low temperature exposure. The entire test matrix plus results at LH_2, LO_2,
and room temperatures is shown in Table 1. The test program not only imposed the
environments singly at various temperatures but also in combinations, with the sequence
varied to determine if it had any effect on system performance.

MAJOR RESULTS. -

1. A 200 cycle expulsion test (Spec. No. 14) in LH_2 indicated that the bellows behaves
   the same at cryogenic temperature as it does at ambient temperature. No indication
   of fatigue-type damage was found.

2. A 45-day storage test in LH_2 indicated that the CRES-347 bellows material is
   completely compatible with the cryogenic liquid. The specimens were free of any
   type of embrittlement or corrosion.

3. The bellows life cycle at cryogenic temperatures is improved over that at ambient
   temperature.

4. Variation in the test sequencing had no detectable effect on results.

5. Overall, it has been shown that the metallic bellows operating parameters are
   unimpaired by exposure to either LH_2 or LO_2, and that ambient temperature
   design techniques apply.

COMMENTS. - A too-general interpretation of the second clause in the fifth result
would be unwise. In general cryogenic temperature exposure introduces a whole new
set of design considerations and the current results were for only one size and type of
bellows.

Table 1. Test Matrix and Results

Test Spec.	LH$_2$ Test Sequence					Results
1 2	Pre-test cycling	45-day LH$_2$ Storage	Vibration Testing	Leak Test	Metall. Eval.	Any damage seen was attributed to the vibration test, no evidence of corrosion, did not leak after test, hardness levels typical
3 4	45-day LH$_2$ Storage	Leak Test	Metall. Eval.			No evidence of any type of corrosion or attack, did not leak.
5 6	45-day LH$_2$ Stor.	Vibr. Test	Leak Test	Metall. Eval.		Any damage seen was attrib. to the vibr. test, no evidence of corrosion, did not leak after test, hardness levels typical.
7 8	Vibr. Test	Leak Test	45-day LH$_2$ Stor.	Leak Test	Metall. Eval.	Any damage seen was attrib. to the vibr. test, no evidence of corrosion, did not leak, hardness levels typical.
9 10	Vibr. Test.	Leak Test	Metall. Eval.			The damage was identical to specimens with other test sequences. Hardness levels typ.
11 12	45-day LH$_2$ Stor.	Incipient Buckling	Leak Test	Metall. Eval.		Any damage was attributed to the buckling test, did not leak, no evid. of corrosion.
13	(200) Expulsion Cycling	Leak Test	Expul. cycle to Failure	Metall. Eval.		The test was terminated at 2601 cycles when the weld failed, fatigue cracks were evident in structure.
14	(200) Expulsion Cycling	Leak Test	Metall. Eval.			Did not leak, no fatigue cracks, typical hardness levels.
	LO$_2$ Test Sequences					
15 16 17	Pretest Cycling	Vibr. Testing	Leak Test	Metall. Eval.		Any damage seen was attrib. to the vibr. test, did not leak, hardness levels typical no evidence of corrosion.
18 19	Vibr. Testing	Leak Test	Metall. Eval.			The damage was identical to specimens with other test sequences, hardness levels typ.
20 21	Expulsion Cycling to Failure		Metallurgical Evaluation			#20 failed at 1935 cycles, #21 at 5350 cycles both failures occurred at crest of first convolute.
	Room Temp Test Sequence					
22	Unused Spare	Expulsion cycled to failure				Failed at 856 cycles in the root of second convolute.

APOLLO RCS POSITIVE EXPULSION TANKAGE PRODUCT
IMPROVEMENT PROGRAM: ELIMINATION OF PERMEATION
AND BUBBLE FORMATION, TASK D
Anderson, R.K., Bell Aerospace, NASA CR-114812, NAS9-7182
November 1969

OBJECTIVE. - To eliminate, or reduce, bladder permeation and the associated
problem of bubble formation on the liquid side of the bladder.

PERTINENT WORK PERFORMED. - Permeation test specimens were fabricated by
Dielectrix Corp. from laminates of TFE Teflon/aluminum film/and FEP Teflon
(Table 1). The Teflon coatings were spray-deposited using Apollo and Lunar Orbiter
technology. Samples of each material were subjected to fifty 2% strain cycles with
specimen length recorded after each load application. Stress relaxation and recovery
tests were performed by applying a 2% strain in various environments and recording
stress levels as a function of time. Specimen recovery was measured as a function
of time after removal from the machine. Finally a series of cyclic roll-fold tests
were performed in water until total rupture of the laminates occurred. No permeability
tests were performed on this contract.

Bubble formation tests were performed using degassed N_2O_4 as the propellant and
helium as the pressurant. Model bladders were TFE/FEP Teflon laminates ten
inches in diameter. The test tank was equipped with viewports for visual observation.
Tests were conducted with wet (liquid-saturated) and dry bladders in both the up and
down positions. In the up position the bladder folded around the standpipe creating
sharp material folds.

MAJOR RESULTS. -

1. The 9 mil 20% codispersion/0.5 mil Al / 3 mil TFE laminate displayed the best
   structural properties.

2. Gas bubble formation in a N_2O_4/GHe Teflon bladder system is retarded by soaking
   the bladder. Bubble formation does not appear to be a problem for the present
   configuration Apollo tanks.

3. Bladder permeation rates are shown in Table 2.

Table 1. Laminates Tested

Configuration Number	Laminate Construction
1	3 mil TFE-1/4 mil Al-3 mil FEP
2	3 mil TFE-1/2 mil Al-3 mil FEP
3	9 mil TFE-1/2 mil Al-3 mil FEP
4	6 mil TFE-1/2 mil Al-6 mil FEP
5	9 mil 20% Co-Dispersion-1/2 mil Al-3 mil FEP

Table 2. Comparison of Permeation Rates

Permeant	Model Test		Full-Scale Test		ASTM Permeation Rate for Single Permeant
	Dry Bladder	Wet Bladder	Dry Bladder	Wet Bladder	
Helium	0.012	0.006 - 6 MIL 0.003 - 12 MIL	0.035 (N_2O_4 Tests) 0.045 (MMH Tests)	0.017 (N_2O_4 Tests) 0.045 (MMH Tests)	0.012-0.050
N_2O_4	0.082	0.082-6 MIL 0.041-12 MIL	0.103	0.103	0.008-0.020
MMH	-	-	0.002	0.002	0.001-0.003

NOTE: Units for permeation rates are $scc/in.^2/hr/psi$ for 6-mil Teflon unless otherwise indicated. Temperature is 70°F.

POLYMERIC POSITIVE EXPULSION BLADDERS FOR
LIQUID OXYGEN SYSTEMS
Hoggatt, J. T. , Boeing Co. , NASA CR-72418, NAS3-7952
(Tasks II and III), June 1968

OBJECTIVE. - To determine the capability of polymeric materials as expulsion
bladders to satisfy typical system requirements in a liquid oxygen environment.

PERTINENT WORK PERFORMED. - A total of ten 12-in. diameter spherical bladders
were subjected to LO_2 expulsion testing, and an additional eight to dynamic modes of
excitation. Barrier ply materials selected were 1/2-mil Kapton and 1/4-mil Mylar
films, based on LO_2 impact tests conducted in Task I. A 3-mil Teflon fabric was
selected as an abrasion and substrate ply material, used to reinforce the laminate
and protect the barrier plies. The three bladder construction configurations consisted
of (1) 10 plies with 12 gores per ply, (2) 5 plies with 6 gores per ply and (3) 5 plies
with 12 gores per ply. The fabrication sequence is shown in Figure 1. Bladders
were installed in the test tank and leak checked prior to filling. Leak checks were
performed after every fifth cycle. Each bladder was repeatedly cycled until failure,
defined as a leakage rate at -280F in excess of 200 scc/min. of GHe, or for 25
complete cycles. Four of the bladders, those with only 5 barrier plies, did not
survive the first expulsion cycle, due to tears or ruptures of the laminate.

Slosh, vibration, impact, and burst tests were run on the remaining eight bladders
to study the structural integrity and chemical compatibility of the polymeric bladders
in an LO_2 environment. Slosh frequencies of 0-10 cps, vibration from 10-160 cps,
acceleration up to 4 g's, and blunt impacts up to 216 ft-lbs of energy were imposed,
as well as ballistic penetration by a 30.06 projectile.

MAJOR RESULTS. -

1. Kapton film, FEP-coated Kapton film, and TFE Teflon fabric were found to be
   LO_2 compatible. No evidence of LO_2 incompatibility occurred in any of the
   expulsion tests.

2. The 10-ply, 12-gore Kapton bladders gave the best overall performance, and were
   the only bladders to reach the program goal of 25 cycles with a leakage rate less
   than 200 scc/min.

3. The fill efficiency (LO_2 volume/tank volume) and expulsion efficiency of all bladders
   averaged 84 and 82 percent, respectively. Values of 99 and 98 percent, respectively,
   were obtained with water at room temperature.

4. Bladders withstood slosh and impact loadings without detriment. Lateral vibrational
   failures resulted from inadequate support of the bladder, and could be remedied by
   a slight redesign.

Tape Adhesive

Gore Segments

Layup Hemisphere

GORE LAYUP

GORE PATTERNS
Cut From Flat Sheet

Mandrel

LAYUP OF SINGLE BLADDER PLY

▷1

Helium in

Sealing
Patch

Stem

Stems Installed

Mandrel Removed

Adhesively Sealed

BLADDER LEAK CHECK

COMPLETED BLADDER

▷ Additional plys are layed up in
same manner, Each ply is ind-
ividually helium leak checked
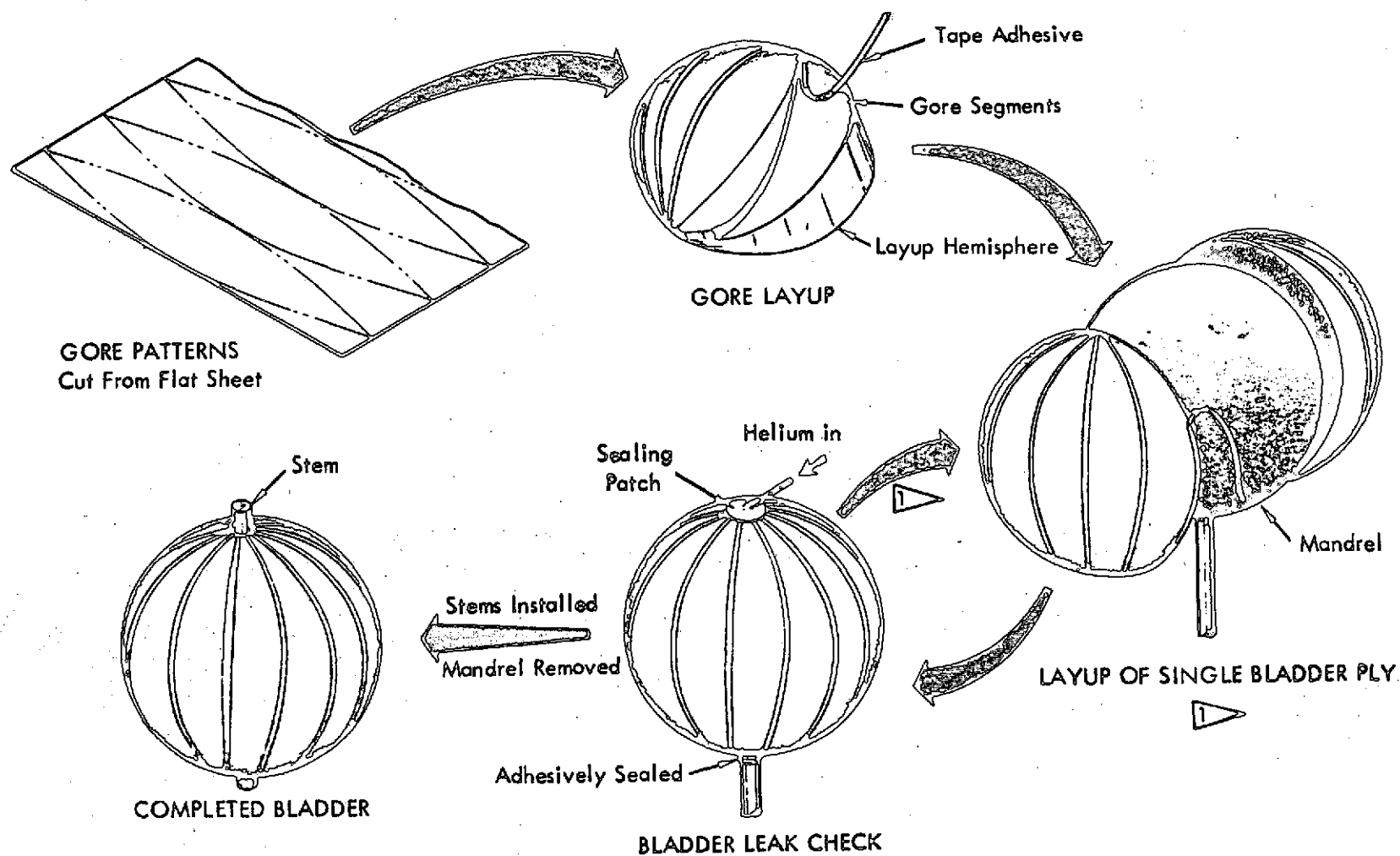
Figure 1. Bladder Fabrication Sequence

DEVELOPMENT OF CRYOGENIC POSITIVE EXPULSION BLADDERS
Pope, D.H., Penner, J.E., Beech, NASA-CR-72115,
NAS3-6288, January 1968

OBJECTIVE. - To consolidate previous achievements in cryogenic laminated-bladder
technology and develop a system capable of 25 failure-free LH_2 expulsion cycles.

PERTINENT WORK PERFORMED. - After a review of previous material investigations,
the following materials were selected for laminate development: Mylar (Type C) film,
Kapton (Type H) film, polyethylene film, Dacron fabric, and Nomex paper. Techniques
for sealing the laminates included adhesive bonding, thermal sealing, and ultrasonic
welding. A total of 95 different laminate configurations were designed and 557 material
samples were fabricated for screening tests, which consisted of an initial peremeability
test, a cryogenic flexibility test, and a final permeability test and failure analysis.
Based on this screening evaluation the five laminates shown in Figure 1 were used to
fabricate a total ot ten 11.5-in spherical bladders for LH_2 expulsion testing. The
design consisted of twelve equal gore sections and a four inch cap section. The
bladders were mounted in a 12 liter, spherical, unsilvered glass dewar. Five LH_2
expulsion tests were performed followed by a permeability check. This cycle was
continued until a total of 25 expulsion cycles and 5 permeability checks had been
performed. Eight of the bladders survived the full 25 cycles, but all eight exhibited
post test leakage rates varying from 18 to 28,000 cm^3 of GHe per minute (Table 1).
Bladder B206 produced the best all-around and most trouble-free performance,
although not the lowest leak rate.

MAJOR RESULTS. -

1. The goal of 25 failure - free expulsion cycles was not achieved.

2. Almost all of the operational problems of these multi-ply bladders can be attributed
   partly or entirely to interply inflation.

3. Outward expulsion (liquid outside bladder) virtually eliminated flow, fill, and
   expulsion problems due to interply inflation.

4. Satisfactory expulsion performance (avg. of 85%) was not as difficult to attain as
   satisfactory LH_2 fill performance (avg. of 71%). Percentages refer to the nominal
   capacity of the bladder.

5. Extensive data on bladders composed of ten or more individual plys has been
   obtained.

Table 1

TABULATION OF EXPULSION TEST RESULTS
(Based on inward expulsion testing observations)

PARAMETERS		B101	B102	B201	B202	B203	B204	B205	B206	B207	B208
1. LH₂ CYCLES											
	Number Completed	25	25	5	25	15	25	25	25	25	25
	% Expulsion	98	82	95	81	80	67	86	95	95	95
	% Expulsion - Last 10 Cycles	99	68	--	93	85	91	94	95	98	90
	Expulsion Behavior	Excel	Poor	Good	Fair	Good	Fair	VyGd	Excel	Poor	Fair
	% Fill	97	78	96	40	77	73	99	99	13	36
	Fill Behavior	Poor	Poor	Good	Poor	Fair	Fair	Excel	Excel	Poor	Poor
	Flow Characteristics	Poor	Poor	Excel	Good	VyGd	Good	Excel	Excel	Good	Good
2. PERMEABILITY											
	Post-Test Rate (cc/min)	3800	18	500	3300	28000	17000	28000	180*	80	240
	Cycle-by-Cycle Pattern	Fair	Good	--	Good	Poor	VyGd	VyGd	Good	VyGd	Good
	Ply-by-Ply Pattern	--	Fair	--	Poor	--	--	--	Good	--**	Fair
3. INTERPLY INFLATION											
	Installation & Removal	Poor	Poor	Good	Fair	VyGd	Poor	Poor	Good	Poor	Fair
	Operational	Poor	Poor	Excel	Fair	VyGd	Fair	Excel	Excel	Poor	Poor
4. PLY CONDITION AFTER TEST											
	Barrier Plys										
	Near Stem	Poor	Good	Excel	Good	Poor	Poor	Poor	Good	--**	Fair
	At Polar Cap	Good	Good	Excel	Good	VyGd	Fair	Excel	Good	--	Excel
	Other Areas	Excel	VyGd	Excel	Good	Good	Excel	Excel	Good	--	Fair
	Substrate Plys										
	Near Stem	Poor	Poor	Good	Good	Excel	Excel	--	--	--	Good
	At Polar Cap	Poor	Poor	Excel	Good	Excel	Excel	--	--	--	Good
	Other Areas	Poor	Poor	Excel	Good	Excel	Excel	--	--	--	Fair
	Comparative Perm.										
	At Stem	--	Poor	Fair*	--	--	Excel	--	Excel	--	Poor
	At Polar Cap	--	Excel	Fair*	--	--	Poor	--	Poor	--	Excel
	% Plys Retained & Effective	55	61	(100)	92	54	54	50	80	92	85

Code for bladder ratings:
Excel (excellent), VyGd (very good), Good; Fair; and Poor

*After repair of stem seal leak, leakage immediately
after LH₂ cycling was 428 cc/min.
**Dissection of bladder after testing not performed.

Figure 1.

BLADDER MATERIALS SELECTED FOR TASK II

Sea-Space Systems, Inc.	B101 B102	*Merfab 10 Plys
	BS 15108 Type 1	.15 Mil Mylar 12 Plys
G. T. Schjeldahl Co.	B201 B202 / BS 15753 Type 1	2 mil Nomex, 3 plys / .25 Mil Mylar, 10 Plys
	B203 B204 / BS 15753 Type 2	2.202 Dacron Sailcloth 3 Plys / .25 Mil Mylar, 10 Plys
	B205 B206 / BS 15753 Type 5	.25 Mil Mylar, 10 Plys
	B207 B208 / BS 15753 Type 7	2 Mil Nomex / .5 Mil Kapton, 10 Plys

Seams   (Schjeldahl)
—— Nomex (GT100) Dacron
—— Mylar (GT300) Kapton

*Merfab (Sea-Space)
2 Plys of .10 Mil Poly
40 Denier HT (Nylon) Fibers
Mylar/Mylar   (S114)
Mylar/Poly   (S110)
Poly/Poly   (Therm.)

MULTICYCLE METALLIC BLADDERS FOR CRYOGENIC
FLUID STORAGE
Gleich, D., ARDE Inc., AFAPL-TR-66-146, AF33(657)-11314,
June 1967.

OBJECTIVE. - To design, fabricate, and test 23-in. diameter multicycling metallic diaphragms for the storage and expulsion of 20 pounds of LH_2 from a spherical tank.

PERTINENT WORK PERFORMED. - Initally, two separate diaphragm configurations were considered; an expanding spherical type and a controlled collapsing hemisphere. The expanding type was discarded due to extreme fabrication difficulties (of the ten specimens processed, only two were considered suitable for test, and both failed prematurely). The hemispherical systems were the thin-shell, wire-reinforced reversing configuration developed by ARDE in prior in-house programs (Figure 1). Bladder structural parameters, shell contour, wire size and spacing, and brazing techniques were systematically studied and improved over the course of the program. AISI 321 stainless was selected as the shell material to avoid cryogenic-temperature embrittlement problems. Procurement problems forced the use of AISI 308 wire, the suitability of which had been demonstrated previously. Copper was selected as the joint brazing material. Six-inch diameter subscale diaphragms were fabricated to check out brazing and structural improvements which were subsequently incorporated into the 23-in. systems.

A total of six of the 6-in. and ten of the 23-in. development units were built and tested in water and LN_2 before the "modified hemispherical" (MH) configuration was developed (Figure 2). Two 6-in. MH units were built and water-tested, followed by fourteen 23-in. MH units tested in water, LN_2, and LH_2. An additional five 23-in. MH units were fabricated and delivered to the Air Force.

MAJOR RESULTS. -

1. The most significant improvements made were the use of the ductile copper braze and the use of a "modified hemispherical" diaphragm contour which reduced strain in the critical equator region and eliminated wire interference problems.

2. The modified-hemispherical diaphragms achieved six, five, and seven successful reversals with LH_2, LN_2, and water, respectively.

3. The MH type of metallic diaphragm has been demonstrated to be suitable for multicycle use with any fluid compatible with annealed stainless steel.
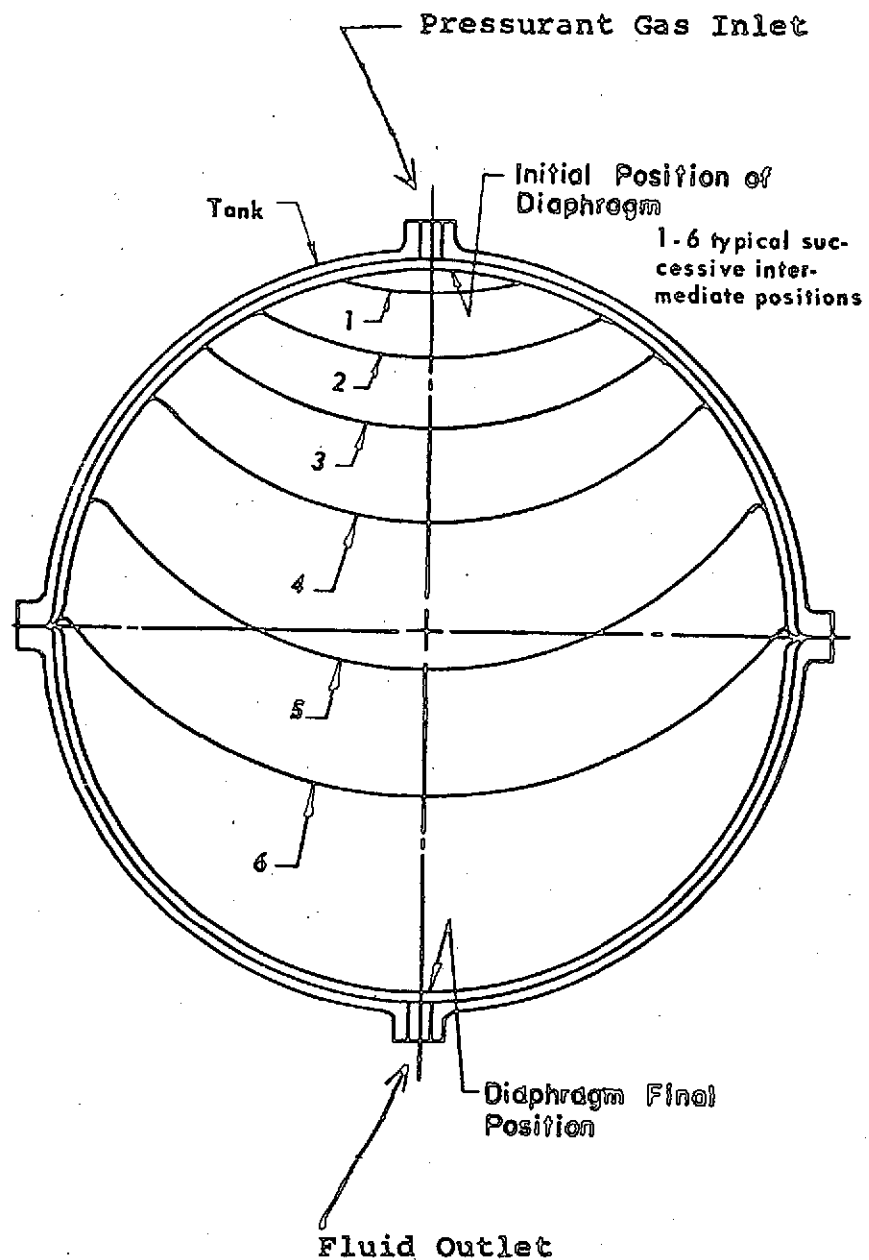
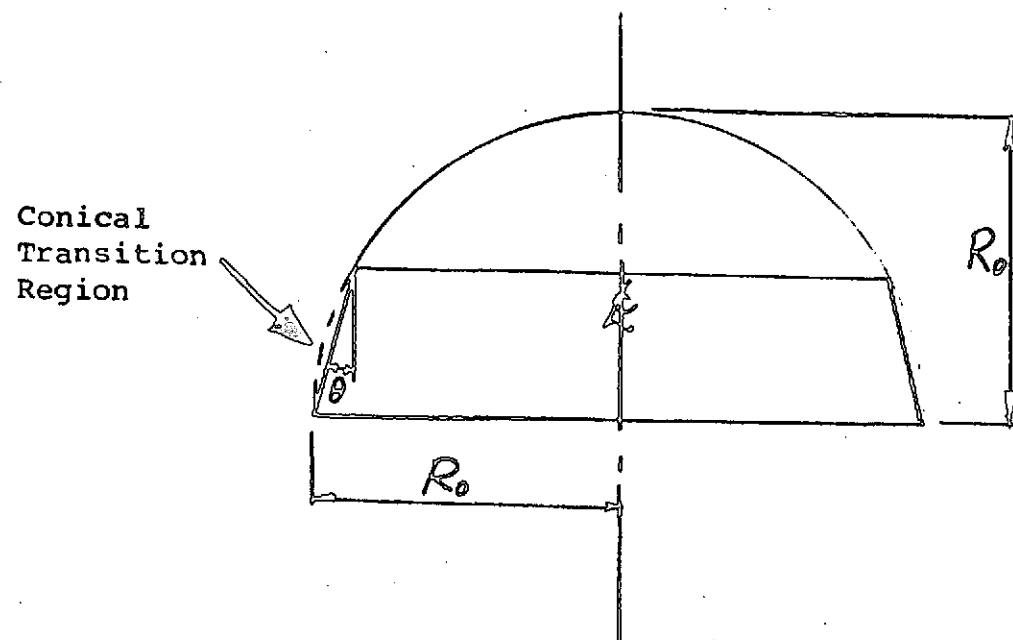Figure 1. Typical Diaphragm Reversal Mode

Figure 2. Sketch of Modified Hemispherical Diaphragm Shell

13.0 OTHER INTERFACE CONTROL AND LIQUID ACQUISITION SYSTEMS

Covering the use of centrifugal, electrical, and acoustic forces for liquid control.

A DIELECTROPHORETIC LIQUID OXYGEN CONVERTER
FOR OPERATION IN WEIGHTLESS ENVIRONMENTS
Blutt, J.R., Hurwitz, M.; Dynatech Corp., AFML-TR-68-21,
July 1968

OBJECTIVE. - To design a dielectrophoretic (DEP) orientation device for a liquid
oxygen converter, to validate the analyses of the converter through experiments, to
demonstrate system safety, and to evaluate the structural integrity of critical
components.

PERTINENT WORK PERFORMED. - The principles of DEP and its effect on dielectric
fluids are discussed, and the requirement to provide an electric field gradient to
move a dielectric liquid toward an outflow port is explained. The so-called "bang-
bang" region at the edge of the electrode array produces an intense field gradient
which has a strong stabilizing effect on the liquid/vapor interface. Tests are described
which show, for the first time, that it is possible to achieve stable DEP orientation
of fluids with dc fields, as well as with ac fields. Four classes of electrode arrays
were evaluated as shown in Figure 1 (liquid drawn to bottom of sphere). Tests
revealed that the parallel disc configuration caused liquid separation, or slug
formation, resulting in high residuals. The other three systems exhibited better,
and equivalent, performance. The fanned disc configuration was selected for the
zero-g experimental models since it was easier to fabricate. A 25 liter spherical,
clear plastic model was constructed for tests with Freon 113 and a 2 liter glass
vacuum Dewar model for LN_2 tests. KC-135 flights gave useful zero-g float times
of 10 to 12 seconds. The results of both zero-g and low-g tests with the 25 liter
device are shown in Figure 2 together with a curve developed from the stabilization
analysis. Materials compatibility, electrical breakdown, and ozone generation tests
were performed to evaluate system safety. A component development and optimization
study resulted in a set of weight equations which are illustrated graphically in Figure 3.

MAJOR RESULTS. -

1. For the first time, it was demonstrated that dc electrical fields, as well as ac
   fields, will provide stable DEP orientation.

2. The stability test results for the 25-liter device compare well with predictions
   (Figure 2).

3. The materials were demonstrated to be compatible with oxygen for the selected
   design. Electrical breakdown and ozone generation problems can be avoided.

COMMENTS. - Stark, 1972, Section 10.0, has questioned the validity of the
conclusions with regard to the safety aspects of the DEP system.

Parallel Discs

Fanned Discs

Nested Cones

Nested Spheres
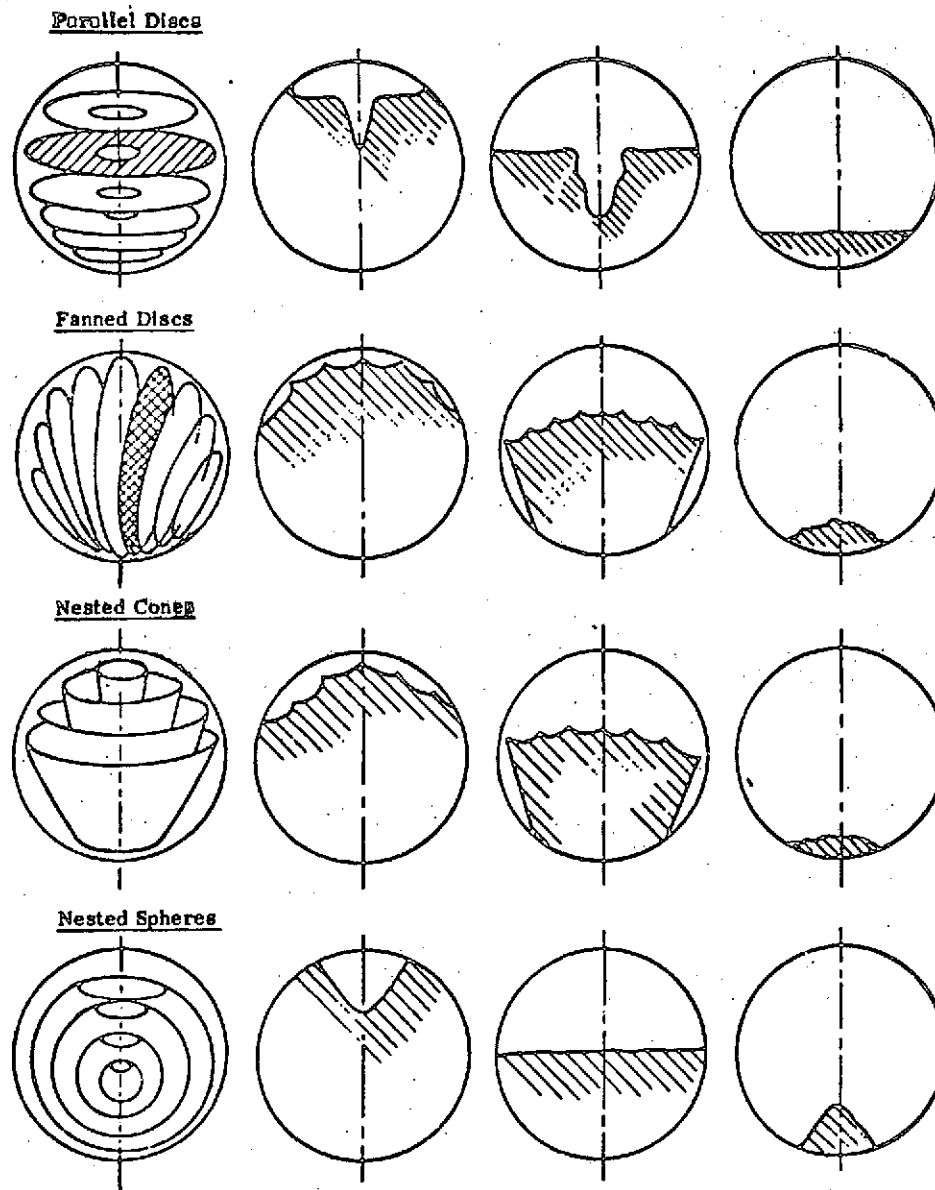
Figure 1. Four Classes of Total Orientation
Electrode Arrays

Note: Each data point represents the best description of the system performance over a number of identical runs.
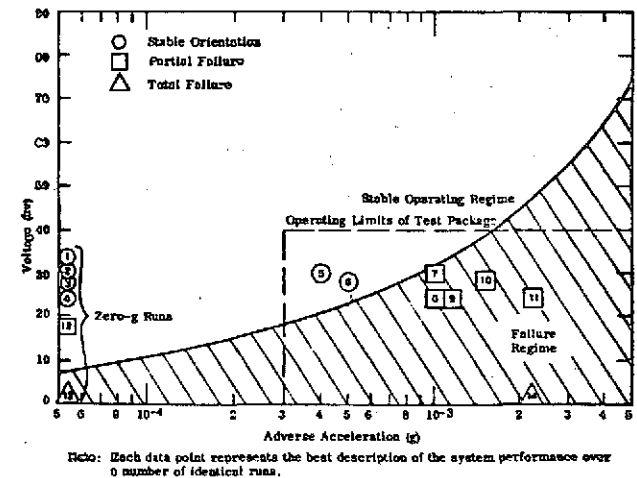
Figure 2. Comparison Between Experimental and
Theoretical Performance of the 25-Liter Dielectro-
phoretic Oxygen Converter with Freon 113 as the
Simulant Liquid
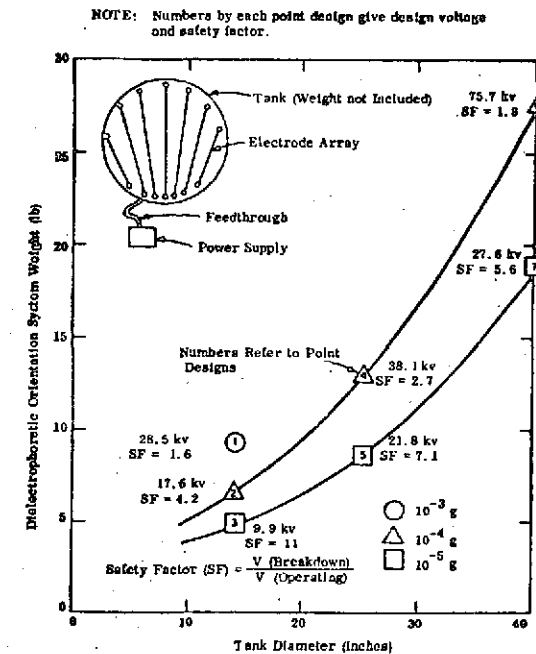
Figure 3. Optimized System Weights for Dielectro-
phoretic Fluid Orientation Systems for Subcritical
Oxygen Converters (V = Voltage)

ORBITAL REFUELING AND CHECKOUT STUDY
FINAL REPORT
Morgan, L.L., et al, LMSC, T1-51-67-21,
NAS10-4606, February 1968

OBJECTIVE. - Define the most feasible and promising conceptual technique(s) for transferring LO_2, LH_2, N_2O_4 and 50% hydrazine/50% UDMH in orbit.

PERTINENT WORK PERFORMED. - In general, analyses, tradeoffs and conceptual designs were based on existing technology. However, with respect to tank rotation for liquid orientation some analyses were performed which are not found elsewhere; at least not for the in-orbit transfer application. Only this aspect of the overall work reported will be summarized. The problem of rotation of a cylindrical tank and liquid about the longitudinal axis is treated. The rotational speed Ω_c to insure collection of liquid on the tank wall was taken from the analysis of Seebold and Reynolds (1965) to be $\Omega_c = \sqrt{(\sigma/\rho R^2) (4 + 5 \rho a R^2/\sigma g)}$, where R is the tank radius, a acceleration in the axial direction and g the gravitational constant. The time for liquid spin-up, T was determined from the analytical work of Greenspan and Howard (1963) to be $T = L/(\nu \Omega_c)^{1/2}$, where L is the tank length. This analysis accounts for momentum transfer induced by secondary flows that exist at the ends of the tank. A purely viscous momentum transfer predicts a characteristic time of $4 R^2/\nu$. Using the Greenspan and Howard analysis the spin-up time for a 33-ft-dia. by 60-ft-long H_2 tank was 11 hours and for the purely viscous case the time was 300 days.

Equations were also developed to account for the use of radial vanes inside the tank to increase the viscous and form drag to reduce the liquid spin-up time. Assuming that the overall drag coefficient ($\bar{C_D}$) can be approximated by a constant average value, the equation for spin-up time was determined to be $T = 36 \pi/(N C_D \Omega_c)$, where N = the number of vanes and C_D is the average drag coefficient for each vane. Assuming these vanes to be screen with $C_D = 0.44$ and N = 4 the spin-up time for the large H_2 tank was determined to be approximately 1-min.

COMMENTS. - Testing was not accomplished here to verify the analyses.

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LIQUID-GAS CYCLONE SEPARATION, Fleeter, S.,
Ostrach, S., Case Institute of Technology, AFOSR
66-1400, June 1966

OBJECTIVE. - Obtain an analytical approximation to the boundary layer discharge of liquid in a liquid-gas vortex separator and verify with experimental data.

PERTINENT WORK PERFORMED. - The analysis is based on a momentum integral method. The basic operation of the cyclone or vortex separator is illustrated in Figure 1, where a mixture of liquid and vapor is introduced tangentially into a cylindrical chamber causing a vortex-like motion which produces a centrifugal force field causing the liquid to move outward. Further, by a properly shaped exit for the liquid; e.g., a conical section, a secondary flow is generated. This secondary flow causes a pressure gradient which directs the liquid toward the apex of the cone where it exits, and should allow the vortex separation and outflow to be accomplished in a low-g field. The following assumptions were made in the analysis; (1) boundary layer flow in the cone is considered separately from the separation process in the cylindrical section, (2) the liquid has constant viscosity and density, (3) the flow is steady, and (4) the only body force acting is that of gravity and the axis of revolution of the separator is parallel to the line of action of gravity.

Testing was accomplished using air and silicone oils of different viscosities, to obtain results over a wide range of Reynolds numbers. The separator was 4.5 in. diameter with a cylindrical section 4.75 in. high. Different cone sections were tested with cone angles of 15° and 45° and outflow diameters of 0.052 to 0.228 in. Testing was performed for outflow with gravity and against gravity (unit inverted from that shown in Figure 1).

MAJOR RESULTS. -

1. An analytical approximation to the secondary flow rate in a vortex separator with a conical outflow section was obtained.

2. Operating with gravity and without evaporation, nearly 100% efficient liquid removal was obtained.

3. Operation against gravity gives evidence that the secondary flow can overcome an adverse body force and thus the unit should operate effectively at low-g. Actual inverted operation at 1-g however, was not efficient due to the considerable adverse static pressure gradient.

COMMENTS. - Using the basic analyses and test results presented here a small water separator for use in a low-g life support shower system was developed (Rosener, et al, 1971) (see Rejections). The final configuration, however, was significantly more complicated than that shown in Figure 1 and incorporated internal baffling to obtain an operational system.
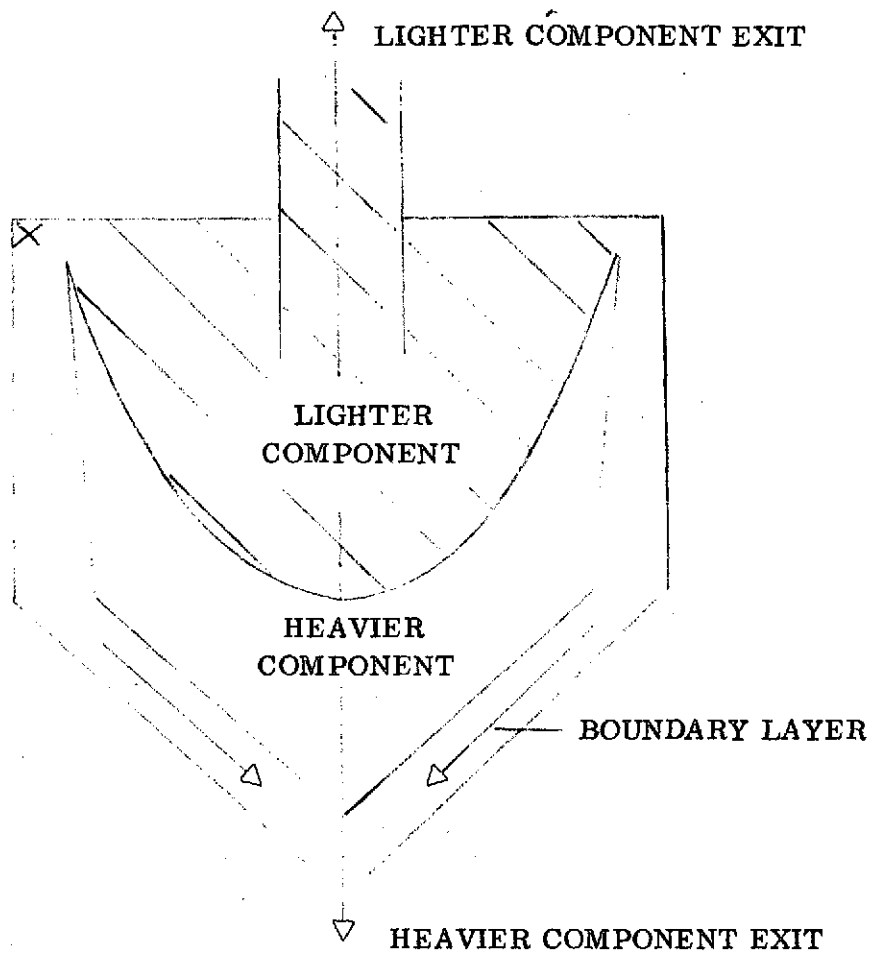
Figure 1. Typical Vortex Separation

COLLECTION OF LIQUID PROPELLANTS IN ZERO
GRAVITY WITH ELECTRIC FIELDS
Blackmon, J.B., MACDAC, Journal of Spacecraft and Rockets, Vol. 2,
No. 3, May–June 1965

OBJECTIVE. - To investigate the theory governing dielectrophoretic (DEP) fluid
control, to conduct simulated and actual zero-g experiments, and to extrapolate results
into the design of two DEP collection systems for a 250,000-lb LH_2/LO_2 space vehicle.

PERTINENT WORK PERFORMED. - Equations for dielectric force fields are developed,
and a comparison between DEP and surface tension forces is made. Surface free-
charge density and the resulting disruptive pressure forces are discussed, with empha-
sis placed on techniques for minimizing such disturbances. Although the maximum DEP
force for a spherical electrode configuration is much greater than that of the cylindrical
configuration due to greater electric field non-uniformity, electrical breakdown will
occur at a lower voltage in the spherical system. Small scale one-g tests were performed
using water drops suspended in a carbon tetrachloride/benzene mixture, followed by
one-second zero-g tests performed with carbon tetrachloride in 250 ml flasks. Eight-
to-ten second low-g ($\pm 0.05g$) tests were performed in an Aerocommander with a
cylindrical electrode system and Dow Corning 200 oil. Tests were performed using
both ac and dc fields, the latter resulting in appreciable stirring of the liquid due to
free charges.

Plausable DEP orientation designs for a 250,000-lb LH_2/LO_2 space vehicle are
discussed. Two separate ac-powered systems, one (I) designed to collect 1000 lb of
LH_2 and 5000 lb of LO_2 over the tank outlets prior to restart (Figure 1) and the other
(II) designed to settle half-full tanks (Figure 2), are compared. Resulting weight
estimates are shown in Table 1. An auxiliary propulsion system designed for one
restart and 15 vent cycles would, by comparison, weigh 2200 lb. The cylindrical
electrode system collects the liquid from the tank walls to the center electrode, there-
by imposing an insulating gas layer between the tank wall and liquid (Figure 3). DC
fields could also be used to reduce temperature stratification, and tank pressure, by
inducing free convection currents to stir the tank.

MAJOR RESULTS. -

1. Due to the problem of free charge disturbances in dc fields, only ac fields may be
   used for stable collection of liquids.

2. DEP systems have been shown to have a very low weight as compared to auxiliary
   propulsion systems for propellant orientation.

3. Propellant weight savings due to liquid orientation to the center of the tank and
   destratification by stirring more than offset the weight of the DEP system.

Table 1. Dielectrophoretic propellant collection
System Weights

Weight	System I (1000-lb LH_2/5000-lb LO_2), lb		System II (half tank), lb	
	LH_2	LO_2	LH_2	LO_2
Electrode	21	11	51	24
Insulation	15	70	42	70
Generator	15	30	30	30
Monofilament support	5	5	5	5
Battery	4	4	4	4
Total	60	120	132	133
Total system (for LH_2 and LO_2 tanks)	180		265	

Figure 1. Electrode Configuration I

Figure 2. Electrode Configuration II
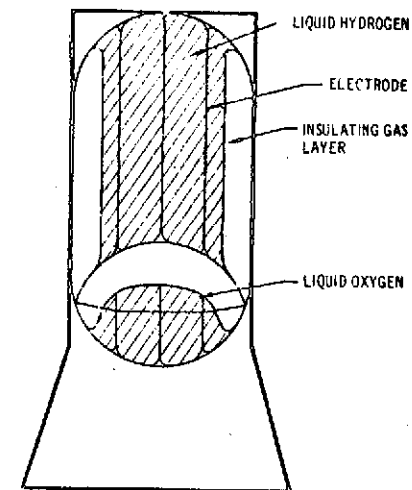
Figure 3. Propellant Positioning for Decreasing Boil-Off Loss

APPENDIX A

AUTHOR INDEX OF SUMMARIZED REPORTS

Anon., "Modular Nuclear Vehicle Design, Vol. IV - Asymmetric Propellant Heating Computer Program, " September 1968, p. 6-10.

Anon., "Propellant Quantity Gauging System Under Zero-g, " August 1971, p. 4-8.

Anon., "Design, Development and Manufacture of a Breadboard Radio Frequency Mass Gauging System, January 1972, p. 4-6.

Adams, R. G., et al, "Performance Characteristics of Liquid-Vapor Sensors Operating in a Reduced Gravity Environment, " May 1969, p. 5-10.

Allgeier, R. K., "Subcritical Cryogenic Storage Development and Flight Test, " February 1968, p. 4-12 and 7-16.

Anderson, R. K., " Apollo RCS Positive Expulsion Tankage Product Improvement Program: Elimination of Permeation and Bubble Formation, Task D, " November 1969, p. 12-12.

Aydelott, J. C., "Effect of Gravity on Self-Pressurization of Spherical Liquid-Hydrogen Tankage, " December 1967, p. 6-14.

Balzer, D. L., et al, "Advanced Propellant Management System for Spacecraft Propulsion Systems, " September 1969, p. 11-38.

Barksdale, T. R., Paynter, H. L., "Design, Fabrication and Testing of Subscale Propellant Tanks With Capillary Traps, " March 1968, p. 11-40.

Barksdale, T. R., et al, "Advanced Propellant Management System for Spacecraft Propulsion Systems, " February 1969, p. 10-10.

Benning, M. A., et al, "Analysis, Design, and Development of a Partial Hydrogen Reliquefier, " October 1972, p. 9-2.

Berenyi, S. G., et al, "An Experimental Investigation of the Effect of Gravity On a Forced Circulation Pattern in Spherical Tanks, " April 1968, p. 8-10.

Blackmon, J. B., "Collection of Liquid Propellants in Zero Gravity With Electric Fields, " May-June 1965, p. 13-8.

Blackmon, J. B., Castle, J. N., "An Integrated Start Tank for Cryogenic Propellant Control, " November 1970, p. 11-22.

Blackmon, J. B., Gaubatz, W. A., "Design, Fabrication, Assembly, and Test of a Liquid Hydrogen Acquisition Subsystem, " May 1974, p. 11-4.

A-2

Blatt, M. H., "Empirical Correlations for Pressure Rise in Closed Cryogenic Containers," June 1968, p. 6-12.

Blatt, M. H., et al, "Low Gravity Propellant Control Using Capillary Devices in Large Scale Cryogenic Vehicles, Phase I Final Report," August 1970, p. 11-26.

Blatt, M. H., et al, "Low Gravity Propellant Control Using Capillary Devices in Large Scale Cryogenic Vehicles, Phase II Final Report," August 1970, p. 11-28.

Blatt, M. H., et al, "Low Gravity Propellant Control Using Capillary Devices in Large Scale Cryogenic Vehicles Design Handbook," August 1970, p. 11-30.

Bliss, J., "MOL Propellant Gauging System," May 1969, p. 4-10.

Blutt, J. R., Hurwitz, M., "A Dielectrophoretic Liquid Oxygen Converter for Operation in Weightless Environments," July 1968, p. 13-2.

Bovenkerk, P. E., "Zero-Gravity Test of an Advanced Surface-Tension Propellant Orientation and Ullage Vapor Venting Device," June 1969, p. 7-12.

Bradshaw, R. D., et al, "Evaluation and Application of Data From Low-Gravity Orbital Experiment," April 1970, p. 6-6.

Brennan, J. A., et al, "An Evaluation of Several Cryogenic Turbine Flowmeters," October 1972, p. 5-6.

Bullard, B. R., "Liquid Propellant Thermal Conditioning System Test Program," July 1972, p. 7-2 and 8-4.

Bupp, F. E., "Development of a Zero-G Gauging System," January 1974, p. 4-2.

Burge, G. W., Blackmon, J. B., "Study and Design of Cryogenic Propellant Acquisition Systems, Vol. I - Design Studies," December 1973, p. 11-6.

Burge, G. W., Blackmon, J. B., "Study and Design of Cryogenic Propellant Acquisition Systems, Vol. II - Supporting Experimental Program," December 1973, p. 11-8.

Cady, E. C., "Study of Thermodynamic Vent and Screen Baffle Integration for Orbital Storage and Transfer of Liquid Hydrogen," August 1973, p. 11-14.

Canning, T. N., "Heater-Mixer for Stored Fluids," August 1972, p. 8-2.

Coulbert, C. D., Yankura, G., "Survey of Materials and Hydrazine Propulsion Systems in Multicycle Extended Life Applications," September 1972, p. 12-4.

Daunt, J. G., et al, "Investigation of Gas Liquefiers for Space Operation, " August 1963, p. 9-6.

DeBrock, S. C., "A Survey of Current Developments in Surface Tension Devices for Propellant Acquisition, " June 1970, p. 11-32.

DeBrock, S. C., "Similarity Testing of Spacecraft Capillary Propellant Management Systems, " November 1973, p. 11-10.

Dowdy, M. W., DeBrock, S. C., "Selection of a Surface Tension Propellant Management System for the Viking 75 Orbiter, " November 1972, p. 11-20.

Epstein, M., Anderson, R. E., "An Equation for the Prediction of Cryogenic Pressurant Requirements for Axisymmetric Propellant Tanks, " August 1967, p. 6-16.

Fester, D. A., "Acquisition/Expulsion System for Earth Orbital Propulsion System Study, Vol. 5; Earth Storable Design, " October 1973, p. 11-12.

Fleeter, S., Ostrach, S., "Liquid-Gas Cyclone Separation," June 1966, p. 13-6.

Gleich, D., "Multicycle Metallic Bladders for Cryogenic Fluid Storage, " June 1967, p. 12-18.

Gluck, D. F., "Propellant Position Control by Capillary Barriers During Spacecraft Rotational Maneuvers, " March 1970, p. 11-36.

Gluck, D. F., "Transient Flow in Capillary Systems, " March 1973, p. 3-6.

Gross, L. A., "An Experimental Investigation of Two-Phase Liquid Oxygen Pumping, " November 1973, p. 3-4.

Heller, W., Cadwallader, E. A., "Positive Expulsion, " May 1971, p. 10-8.

Hoggatt, J. T., "Polymeric Positive Expulsion Bladders for Liquid Oxygen Systems, " June 1968, p. 12-14.

Hoggatt, J. T., "Investigation of the Feasibility of Developing Low Permeability Polymeric Film," December 1971, p. 12-8.

Hord, J., Voth, R. O., "Tabulated Values of Cavitation B-Factor for Helium H_2, N_2 F_2, O_2, Refrigerant 114 and H_2O, " February 1971, p. 3-12.

Howard, F. S., "Zero Gravity Liquid Transfer Screen, " July 1973, p. 10-2.

Jensen, H. L., et al, "Investigation of External Refrigeration Systems for Long Term Cryogenic Storage," February 1971, p. 9-4.

Kaminskas, R. A., Malone, D. J., "Development of isothermal Rigs, Final Report," April 1973, p. 5-6.

Lange, R. L., Hughes, J. T., "Evaluation of Metallic Positive Expulsion Bellows Operating Parameters With Cryogenic Propellants," July 1971, p. 12-10.

Lipa, J. A., et al, "Research at Stanford on the Containment of Liquid Helium in Space by a Porous Plug and On a Long Hold-Time Dewar for the Gyro Relativity Experiment," March 1972, p. 7-6.

Mann, D. B., "ASRDI Oxygen, Technology Review, Vol. VI, Flow Measurement Instrumentation," 1974, p. 5-2.

Manson, L., Miller, W. S., "A Study of Cooldown of Metals, Flow Instability, and Heat Transfer in Two-Phase Flow of Hydrogen," February 1968. p. 3-18.

Martin, J. W., Green, H. E., "Elastomers for Fluid Rocket Propellant Containment," October 1973, p. 12-2.

Merte, H., et al, "Transient Pressure Rise of a Liquid-Vapor System In a Closed Container Under Variable Gravity," September 1970, p. 6-4.

Mitchell, R. C., et al, "Study of Zero-Gravity, Vapor/Liquid Separation," January 1966, p. 7-20.

Morgan, L. L., et al, "Orbital Refueling and Checkout Study, Final Report," February 1968.

Orton, G. F., "Simulated Flight Vibration Testing of a Surface Tension Propellant Expulsion Screen," October 1970, p. 11-24.

Page, G. R., Tegart, J. R., "Vent Free Fluorine Feed System Analysis," September 1969, p. 7-8.

Papell, S. S., et al, "Buoyancy Effects on Critical Heat Flux of Forced Convective Boiling in Vertical Flow," October 1966, p. 3-22.

Parmley, R. T., "In-Space Propellant Orientation and Venting Experiments, Phase I," October 1966.

Paynter, H. L., Page, R. G., "Acquisition/Expulsion System for Earth Orbital System Study, Final Report — Vol. II Cryogenic Design," June 1973, p. 11-16.

Paynter, H. L., Page, R. G., "Acquisition/Expulsion System for Earth Orbital Propulsion System Study, Final Report, Vol. III, Cryogenic Test," June 1973, p. 11-18.

Paynter, H. L., "Experimental Investigation of Capillary Propellant Control Devices for Low Gravity Environments," June 1970, p. 11-34.

Pope, D. H., Penner, J. E., "Development of Cryogenic Positive Expulsion Bladders," January 1968, p. 12-16.

Poth, L. J., et al, "A Study of Cryogenic Propellant Mixing Techniques, Vol. I, Mixer Design and Experimental Investigations, Vol. II, Experimental Data," November 1968, p. 8-8.

Scheiwe, J. P., Cho, B. Y., "Nucleonic Measurements of Cryogenic Densities and Qualities," July 1967, p. 5-14.

Schuler, A. L., et al, "Storability Demonstration Propellant Feed Systems," October 1967, p. 10-12.

Schwartz, R., "Saturn S-II Advanced Technology Studies, Study 8, Cryogenic Acquisition and Transfer," December 1971, p. 10-6.

Sexton, R. E., et al, "In-Space Propellant Logistics," June 1972, p. 2-2 and 7-4.

Shen, P. S., Jao, Y. W., "Pressure Drop of Two-Phase Flow in a Pipeline With Longitudinal Variations in Heat Flux," June 1969, p. 3-14.

Sinclair, D. H., et al, "Cryogenic Temperature Measurement Using Platinum Resistance Thermometers," April 1968, p. 5-12.

Smetana, J., Wenger, N. C., "Instrumentation for Liquid Hydrogen Density Measurements Using an Open-Ended Microwave Cavity," July 1971, p. 5-8.

Smith, R. V., "Some Idealized Solutions for Choking, Two-Phase Flow in Hydrogen, Nitrogen, and Oxygen," August 1962, p. 3-26.

Smith, R. V., "Two-Phase, Two-Component Critical Flow in a Venturi," March 1972, p. 3-10.

Smith, R. V., et al, "Critical Two-Phase Flow of Cryogenic Fluids," January 1973, p. 3-8.

Sparks, L. L., "ASRDI Oxygen Technology Survey, Vol. IV, Low Temperature Measurement," 1974, p. 5-4.

Stark, J. A., Blatt, M. H., "Zero Gravity Prototype Vent System, October 1967, p. 7-18 and 8-12.

Stark, J. A., Blatt, M. H., "Analysis of Zero Gravity Receiver Tank Vent Systems, " July 1969, p. 7-10.

Stark, J. A., "Study of Low-Gravity Propellant Transfer, " June 1972, p. 12-6.

Stark, J. A., "Study of Low Gravity Propellant Transfer , " June 1972, p. 10-4 and 2-4.

Sterbentz, W. H., et al, "Liquid Propellant Thermal Conditioning System — Final Report, " August 1968, p. 7-14.

Steward, W. G., "Transient Flow of Cryogenic Fluids, " 1968, p. 3-16.

Stochl, R. J., DeWitt, R. L., "Pressurant Gas Requirements for the Pressurized Discharge of Liquid Hydrogen from Propellant Tanks, " June 1969, p. 6-8.

Stochl, R. J., "Gaseous-Helium Requirements for the Discharge of Liquid Hydrogen From A 3.96-Meter (13-ft) Diameter Spherical Tank, " December 1970, p. 6-2.

Streeter, V. L., Wylie, E. B., "Waterhammer and Surge Control, 1974, p. 3-2.

Symons, E. P., "Wicking of Liquids in Screens, " May 1974, p. 11-2.

Thompson, J. F., Nein, M. E., "Experimental and Analytical Studies of Cryogenic Propellant Tank Pressurant Requirements, " February 1966, p. 6-18.

Vanderveld, W. E., "An Experiment to Test Low Level Accelerometers, " 1963, p. 5-16.

Van Hook, J. R., Poth, L. J., "Study of Cryogenic Fluid Mixing Techniques — Final Report, " September 1970, p. 8-6.

Vernon, R. M., Brogan, J. J., "A Study of Cryogenic Container Thermodynamics During Propellant Transfer, " November 1967, p. 3-20.

Wood, D. J., et al, "Digital Distributed Parameter Model for Analysis of Unsteady Flow In Liquid-Filled Lines, " May 1965, p. 3-24.

Yoshikawa, H. H., Madison, I. B., "Review of Orbital Propellant Transfer Techniques and the Feasibility of a Thermal Bootstrap Propellant Transfer Concept, " December 1971, p. 2-6.

APPENDIX B

REPORTS REVIEWED AND NOT SUMMARIZED

This section contains a listing of reports which were reviewed, but not summarized, including reasons for not summarizing. The listing is by category and author. The categories are basically the same as described for the detailed summaries. The page location of each category is presented below.

GENERAL

Anon., "An Analysis of Chemical Upper Stages for NASA Scientific Missions,"
NASA-LeRC, NASA TM X-52127, 1965.

    No new technology data are generated by this study which would be applicable to
in-orbit fluid transfer.

Anon., "Documentation for the Zero-g Fluid Handling Test Program," GE, NASA
CR-115616, X72-10411, Contract No. NAS9-10741, November 1970.

    Deals with equipment to be used in the performance of biochemical, hematological,
and microbilogical experimentation and data pertinent to in-orbit transfer is not.
presented.

Anon., "Final Report Advanced Orbital Launch Operations, Volume VI, Propellant
Transfer Studies," LTV, 00.368, Contract No. NAS8-5344, May 1964.

    This work has been superseded by more recent data.

Anon., "Modular Nuclear Study," LMSC, Contract No. NAS8-20007, March 1966 to
February 1968.

    Other than Volume IV of Phase I, which is summarized, no new technology data
was found which was significant to in-orbit fluid transfer. The study consisted
basically of design trade-offs and vehicle analyses using existing technology.

Anon., "Payload Optimization Factors for Storage of Liquid Hydrogen in a Low Gravity
Environment," MACDAC, AIAA Paper No. 69-1007, M/F 69A40381, September 1969.

    This is only a paper study using existing data and does not add to the state-of-the-
art of the technology required for in-orbit fluid transfer.

Anon., "Reusable Nuclear Ferry Vehicle - Preliminary Design Study," LMSC,
LMSC-B007429-I, II, III, Contract No. NAS8-5020, February 1964.

    Work in technology areas of interest is based on existing information and new
technology data of significance to the current program is not presented.

Anon., "European Space Tug - Vol. 3 - Propellant and Propulsion," Hawker Siddeley,
HAS TP7264, N73-19903, August 1971.

    Tradeoffs, analyses and weights are based on existing technology information.

Anon., "Study of Orbital Launch Operations," LTV, 00.26, Contract No. NAS8-853,
January 1962.

    This work as it pertains to in-orbit fluid transfer has been superseded by more
recent work.

Abdalla, K. L., et al, "Liquid Transfer Demonstration on Board Apollo 14 During Transearth Coast," NASA-LeRC, NASA TM X-2410, November 1971.

Photographic coverage is only qualitative and no comparisons are given between theory and test data.

Ackerman, J. W., et al, "Shuttle: Reaction Control System. Cryogenic Liquid Distribution System: Study," NASA-JSC, NASA TM X-68913, N73-16765, January 1972.

Tradeoffs and analyses are based on existing technology data.

Adkins, A. W., et al, "Storage, Servicing, Transfer, and Handling of Hydrogen," ADL, AFFTC Tech. Report 61-18, Contract No. AF33(616)-7330, May 1961.

The primary application is to ground handling and technology data of significant interest to the current program is not presented.

Allgeier, R. K., et al, "Cryogenic Storage Systems for Earth-Orbital and Mars-Flyby Missions," NASA-JSC, NASA TN D-4619, July 1968.

General information only with no significant technology data presented.

Bixler, W. D., Masters, J. N., "Composite Tanks With Load Sharing Liners," Boeing, 2-1107-3600-388, Contract No. NAS3-14380, October 1971.

Deals strictly with tank construction details, which is not within the scope of the current study.

Booth, G. H., "In-Orbit Assessment Report," Vol. 2, ESRTC, Noordwijk, Netherlands, ESRO-TR-4-ESTEC, N/F 74N16567, July 1973.

This report contains an assessment of the performance of the various spacecraft systems during the first six months of orbit of the HEOS-1, launched in December 1968, but does not contain any data on low-g fluid system performance.

Boretz, J. E., "Orbital Refueling Techniques," TRW, AIAA Paper No. 69-564, June 1969.

General survey only. None of the technology areas are covered in sufficient detail and the data are not current enough to be of significant use to the present program.

Burge, G. W. System Effects on Propellant Storability and Vehicle Performance, MACDAC, AFRPL-TR-66-258, Contract No. AF04(611)-10750, October 1966.

Analyses and tradeoffs were based on existing technology information. This report does not cover the testing phase of the program. (Ref. Burge, 1968 and Kelly, 1970).

Burge, G. W., "System Effects on Propellant Storability and Vehicle Performance," MACDAC, AFRPL-TR-68-227, Contract No. AF-04(611)-10750, December 1968.

Essentially all the significant test data obtained was associated with 1-g tank pressurization which, for purposes of the current program is covered adequately elsewhere.

Carr, R. H., "Applications of Cryogenic Technology," Vol. 5, Scholium International, Inc., Cryogenic Society of America Conference, October 1972.

None of the papers presented were of interest to the current study.

Chandler, W. A., "Cryogenic Storage for Space Electrical Power," NASA-JSC, Astronautics and Aerospace Engineering, May 1963.

This is very early work in the field, which has been superseded by later and more complete information.

Davis, M. L., et al, "The Development of Cryogenic Storage Systems for Space Flight," NASA-JSC, NASA SP-247, 1970.

This is a good overview of the work accomplished and the resulting cryogenic storage systems for Apollo life support and power systems. However, technology details are not presented in depth and are covered better by summaries and/or reivews of the source material.

DeLand, R. E., et al, "Space Storable Propellant Module Thermal Control Technology," Vol. I (OF_2/B_2H_6 Propulsion Module), Vol. II (F_2/N_2H_4 Propulsion Module), TRW, 14051-6009-R0-000, Contract No. NAS7-750, March 1971.

Existing technology was used to accomplish trade-offs for the specific vehicle requirements of this program.

DesCamp, V. A., et al, "Study of Space Station Propulsion System Resupply and Repair," MMC, MCR-70-150, Contract No. NAS8-25067, June 1970.

Trade-offs and data presentation are based on existing technology.

DeWitt, R. L., et al, "Fluid Coupling," NASA, U.S. Patent No. 3,170,486, February 1965.

This is a detailed piece of hardware which represents only one small part of the overall transfer system.

Erichsen, P., "Performance of Satellite Propellant Storage Systems," ESRTC, Noordwijk, Netherlands, ESTR-TN-117-ESTEC, N74-16481, October 1973.

Deals with compressed gas storage systems with general discussions and does not advance the state-of-the-art.

Fradkov, A. B., "Preserving Liquid Helium During Spaceflight," Academy of Sciences, Moscow, Instrum. Exp. Tech. (USSR), No. 6, 1607-8, UDC 536.581.3, December 1969.

Experiments on the storage of liquid helium in a cryostat on an orbiting satellite are briefly reported, however, the data are not sufficient to add anything to the state-of-the-art of technology required for in-orbit fluid transfer.

Haglund, R., Gould, R., "Cryogenic Storage System," NAR, SID 65-1526, Contract No. NAS9-5017, December 1965.

The work reported deals mainly with tankage details and did not get past the design stage.

Harris, E., "Design of H_2-O_2 Space Shuttle APU," Vol. 1, AiResearch, NASA CR-121214, Micro Folio N74-15737, January 1974.

Information specifically related to shuttle with no basic technology information that can be extrapolated to other systems.

Harris, E., "Design of H_2-O_2 Space Shuttle APU," Vol. 2, AiResearch, NASA CR-134485, N74-15738, January 1974.

Contains Space Shuttle APU system analysis and computer printouts of system performance without basic technology information useful to low g fluid transfer.

Heald, D. A., et al, "Orbit-to-Orbit Shuttle Propellant Integration and Handling Study," EAFB, AFRPL-TR-71-117, December 1971.

Work is based on existing technology data, with no new pertinent contributions made which would be applicable to in-orbit fluid transfer.

Hogan, L. R., et al, "Orbital Operations Study," NAR, N72-32804, Contract No. NAS9-12068, May 1972.

This was primarily an operations study and significant advancements were not made in the state-of-the-art of the individual technologies associated with in-orbit fluid transfer and overall transfer data of interest are the same as in Sexton, et al (1972), which is summarized.

Kelly, T. J., "Testing of a Cryogenic Propellant Subsystem in a Simulated Space Environment," AFRPL, AD 871 153, AFRPL-TR-70-5, March 1970.

The only data of significance was that associated with 1-g tank pressurization which, for purposes of the current program, is covered adequately elsewhere.

Kuhrt, W. A., "A Survey of Future Space Propulsion Systems," United Aircraft, Annals New York Academy of Sciences, Vol. 163, pp. 453-465, September 1969.

Information is concentrated in the engine area and no technology data are presented which would be useful to in-orbit fluid transfer.

Morgan, L. L., "Parametric Studies of Orbital Fluid Transfer," LMSC, AIAA Paper No. 69-565, June 1969.

This work is reported in greater detail in contract reports, i.e., Morgan, et al, 1968, NAS10-4606, which is summarized

Morgan, L. L., et al, "Orbital Tanker Design Data Study," LMSC, LMSC-A748410, Contract No. NAS8-11326, Vol. I, II, III and IV, May 1965.

This study did provide some interesting parametric data on fluid transfer systems, however, the work done was based on existing information and no actual advancement was made in the individual technology areas. With respect to the overall systems aspects, later studies having more current information have been performed and are reviewed elsewhere.

Morgan, L. L., et al, "Shuttle Cryogenics Supply System Optimization Study," LMSC, LMSC-A991396, Contract No. NAS9-11330, June 1973.

This is a multi-volume report covering overall optimization and integration of all potential space shuttle cryogenic systems, however, only existing technology data or technology developed elsewhere was used in the study.

Morita, W. H., et al, "Feasibility of Modifying the S-II Stage as an Injection Stage for Manned Planetary Flyby," NAR, SID 67-275-1, 2, 3, 4, (Vol. I, II, III and IV) Contract No. NAS8-18031.

The systems presented here are based on existing technology or assumptions about what could be built. No new technology data of interest to the current study are presented.

Naugle, J. E., "The Space Shuttle Payload Planning Working Groups," Vol. 10, NASA, NASA-TM X-69457, N74-11527-Micro Folio, May 1973.

General discussions with specific technology data not given.

Navickas, J., Melton, H. R., "Thermal/Structural Optimization of Cryogenic Storage Systems," MACDAC, AIAA Paper No. 72-142, January 1972.

Simplified approach to overall thermal control optimization as a paper tradeoff study with no new technology data presented.

Nelson, L. M., et al, "Versatile Upper Stage Final Report," GD/C, GDCA-BNZ71-012, Contract No. NAS7-804, June 1971.

Presents results of a six month study to define a Versatile Upper Stage (VUS) vehicle capable of performing a variety of missions with only existing fluid system technology data used in the study.

Nissim, W., et al, "Design and Systems Analysis of a Chemical Interorbital Shuttle," Final Report, NAR, SD-72-SA-0042-1 thru 5, Contract No. NAS8-27670, May 1972.

Trade-offs, analyses and design are based on existing technology information.

Nissim, W., et al, "S-II Stage Interorbital Shuttle Capability Analysis," NAR, SD 71-245-1, Contract No. NAS7-200, April 1971.

Only existing technology was used in performing this study.

Priem, R. J., "Liquid Rocket Technology for the Chemical Engineer," NASA, NASA-TM X-52695, Micro Folio N70-33892, 1969.

Problems and technical advancements associated with cryogenic liquid rocket propellant systems are discussed in general terms, with no new technology data presented.

Rysavy, G., "Spacecraft Cryogenic Gas Storage Systems," NASA-JSC, NASA TM X-67546, M/F N72-18763, 1971.

This is a general survey paper which is similar to a more extensive report (Davis, et al, 1970, SP-247), which is reviewed elsewhere.

Salvinski, R. J., et al, "Advanced Spacecraft Valve Technology Compilation," Vol. I and II, TRW, Contract No. NAS7-717, Micro Folio No. Vol. I - N70-37560, NASA CR-112789, Micro Folio No. Vol. II - N70-37561, NASA CR-112790, July 1970.

The only information which might be of interest is on a zero-g vent system, which work is presented in Salvinski (1965) reviewed under Vent Systems.

Sexton, R. E., et al, "S-II Stage Orbital Propellant Storage System Feasibility Study," NAR, SD 70-554, Contract No. NAS7-200, March 1971.

In general, only existing technology information was used in this study in the areas associated with in-orbit fluid transfer. Basic transfer system ideas are essentially the same as presented by Sexton, et al (1972) under the In-Space Propellant Logistics Study, which is summarized.

Simon, W. E., et al, "MSC Cryogenics Symposium Papers at NASA Manned Spacecraft Center," NASA-JSC, et al, MSC-04312, May 1971.

These papers were presented basically for the exchange of general information and pertinent work is covered more completely in other technical NASA and contractor reports which are reviewed elsewhere.

Vance, R. W., "Applications of Cryogenic Technology," Aerospace Corp., CRYO 71 Proceedings, 1971.

There was no data presented applicable to space vehicles, space transfer of fluids or low-g fluid behavior.

Whitacre, W. E., "An Analysis of Potential Space Shuttle Cargo-Handling Modes of Operation," NASA-MSFC, NASA TM X-64507, February 1970.

This is only a brief general review, without any specific new technology data presented.

Wiederhorn, C., "The Space Environment and Its Iterations With Liquid Propellants and Their Storage Systems," ADL, C-63270-02-1, Contract No. NAS5-664, September 1961.

Specific data are only presented on the space environment with respect to electromagnetic and particulate radiation and meteoroids

Wilson, D. J., et al, "Orbital Propellant Depot System," LMSC, Advances in Cryogenic Engineering, June 1970.

General discussions only, without specific technology data presented.

Wolfe, R. R., et al, "Orbital Propellant Depot Safety," Vol. I, II, III, Aerospace Corp., ATR-71 (7233)-3, NASA CR-123385, Contract No. NASw-2129, September 1971.

The objective of the study was to provide safety guidelines and requirements for the operation of an Orbiting Propellant Depot . Only discussions and data of a general nature was presented with no specific technology information of use to the present study.

Wood, C. C., Trucks, H. F., "Evaluation of Experimental and Analytical Data for Orbital Refueling Systems," NASA-MSFC, AIAA 5th Propulsion Joint Specialist Conference, Paper No. 69-566, June 1969.

The work presented here is based only on existing technology data.

Ziemke, M. C., et al, "An Early Earth-Orbital Propellant Mission," Chrysler, Institute of American Astronautical Society Southeastern Symposium on Missiles and Aerospace Vehicles, Vol. 2, December 1966.

Presents general discussions only, with no quantitative data pertinent to advancing the state-of-the-art of technology associated with in-orbit fluid transfer.

FLUID LINE DYNAMICS AND THERMODYNAMICS

Anon., "Pressurized Cooldown of Cryogenic Transfer Lines," ADL, C-59879, Special Report No. 106, October 1959.

Due to its similarity with the summarized work of Steward (1968), this report was not summarized.

Bronson, J. C., et al, "Problems in Cool-Down of Cryogenic Systems," Univ. of California/Los Alamos, Advances in Cryogenic Engineering, Vol. 7, p. 198, August 1961.

The information presented in this paper has been superseded by more recent work in this field.

Chenoweth, F. C., et al, "Transient Chilldown of a Single Thick-Walled Tube by Liquid and Gaseous Hydrogen," NASA-LeRC, NASA TN D-4238, November 1967.

Due to inaccuracies in calculated fluid and wall conditions, this material is of questionable use in the design of propellant lines.

Chi, J. W. H., "Cooldown Temperatures and Cooldown Time During Mist Flow," Westinghouse, Advances in Cryogenic Engineering, Vol. 10, p. 330, August 1964.

Tests of the model against slug flow, as opposed to mist flow, showed significant deviations and thus the model cannot be generally applied to the prediction of cooldown times.

Commander, J. C., Schwartz, M. H., "Cooldown of Large-Diameter Liquid Hydrogen and Liquid Oxygen Lines," Aerojet-General, NASA CR-54809, Contract No. NAS3-2555, April 1966.

The object of this study was to investigate the cooldown requirements for the 18-in. diameter LH_2 and LO_2 transfer lines at the M-1 engine test facility, and is too specific to add to the general state-of-the-art.

DiStefano, J. F., Caine, G. H., "Cavitation Characteristics of Tank-Mounted Cryogenic Pumps and Their Predicted Performance Under Reduced Gravity," Pesco, Advances in Cryogenic Engineering, Vol. 7, pp. 227-290, August 1961.

This is early work in the field and the low-g aspects of the problem are only discussed in general terms.

Dorsch, R. G., et al, "Distributed Parameter Analysis of Pressure and Flow Disturbances in Rocket Propellant Feed Systems," NASA-LeRC, NASA TN D-3529, August 1966.

Development of the wave-plan solution presented here is adequately summarized elsewhere.

Duggins, R. K., "The Initiation of Flow From Rest of Liquid in a Pipe-Line With Discrete Gas Pockets," University of Nottingham, A74-11437, International Conference on Numerical Methods in Fluid Dynamics, Southampton, England, September 1973.

This analysis is for a very idealized fluid condition, not pertinent to the low-g technology study.

Edmonds, E. K., Hord, J., "Incipient and Developed Cavitation in Liquid Cryogens," NBS, NBS TN-374, February 1969.

This is a detailed study of one small area associated with fluid transfer which did not warrant summarization for the current program.

Evans, D. G., "Visual Study of Swirling and Nonswirling Two-Phase Two-Component Flow at 1 and 0 Gravity," NASA-LeRC, NASA TM X-725, August 1963.

This study did not investigate the effect of gravity on pressure loss and heat transfer, the most important parameters.

Farrel, E. C, Fenwick, J. R., "POGO Instabilities Suppression Evaluation," Rocketdyne, NASA CR-134500, R-8125, Contract No. NAS8-14382, November 1973.

This phenomenon is not pertinent to low-g fluid transfer.

Grolmes, M. A., Fauske, H. K., "Two-Phase Pressure Drop for Cryogenic Fluids," Argonne, National Lab., 13th International Congress of Refrigeration, September 1971.

For purposes of the current program this subject is adequately covered by Shen and Jao (1969), which report is summarized.

Henry, R. E., and Fauske, H. K., "The Two-Phase Critical Flow of One-Component Mixtures in Nozzles, Orifices, and Short Tubes," Argonne National Lab., ASME Journal of Heat Transfer, p. 179, May 1971.

Pertinent data are covered in more recent reports, e.g., Smith, et al (1973) and Smith (1972) which reports are summarized.

Holster, J. L., Astleford, W. J., "Analytical Model for Liquid Rocket Propellant Feedline Dynamics," SwRI, Journal of Spacecraft and Rockets, p. 180, Contract No. NAS8-25919, March 1974.

This work is associated with engine feedlines and is not significantly applicable to in-orbit fluid transfer.

Holster, J. L., "Liquid Rocket Propellant Feedline Dynamics," SwRI, AIAA Paper No. 73-1286, Contract No. NAS8-25919, November 1973.

This work is associated with engine feedlines and is not significantly applicable to in-orbit fluid transfer.

Hsu, Y. Y., "Review of Critical Flow Rate, Propagation of Pressure Pulse and Sonic Velocity in Two-Phase Media," NASA-LeRC, NASA TN D-6814, June 1972.

This review is similar to that conducted by Smith, et al (1973).

Koestel, A., "Hydrodynamic Problem Areas in Zero Gravity," Thompson Products, Technical Memorandum 1488, November 1959.

This paper discusses fluid flow regimes and liquid/gas interface effects in general terms and does not add to the description of the current state-of-the-art of low-g fluid transfer.   B-10

Leonhard, K. E., et al, "A Comparison of Cooldown Time Between Internally Coated and Uncoated Propellant Lines," GD/C, Advances in Cryogenic Engineering, Vol. 12, p. 331, Contract No. NAS8-20167, June 1969.

The effect of coatings on transfer line cooldown time was covered in the summary of the report by Manson and Miller (1968).

Leonhard, K. E., "Liquid Hydrogen Suction Line Insulation Research and Development," GD/C, GDC-DDB66-007, Contract No. NAS8-20167, July 1966.

The portion of this study dealing with line insulation was summarized under "Cryogenic Thermal Control Technology." The effect of line internal coatings was covered in the summary of the report by Manson and Miller (1968).

Liebenberg, D. H., et al, "Cooldown of Cryogenic Transfer Systems," Univ. of California, Los Alamos, AIAA Paper No. 67-475, July 1967.

This paper is a good general discussion of many aspects of transfer line cooldown, however, the material presented does not add to the state-of-the-art in this field.

Liebenberg, D. H., "Cooldown of Cryogenic Transfer Lines," Univ. of California, Los Alamos, LA-3426-MS, Contract W-7495-ENG-36, November 1965.

This report describes predictions of and test data for the cooldown of 10 and 12-in diameter cryogenic transfer lines at the Nuclear Rocket Development Station of the Los Alamos Scientific Laboratory and is too specific to contribute to the general state-of-the-art.

Ludtke, P. R., Voth, R. O., "A Study of LC-39 Cryogenic Systems," NBS, NBS Report 10705, Project 275.05-2750458, September 1971.

This work is too specific to add to the general state-of-the-art.

Merino, F., "Simulation of and Recommendations for Centaur Vehicle Pre-Start and Chilldown Flow Sequences," GD/C, AY62-0013, Contract No. AF18(600)-1775, August 1962.

The objective of this study was to develop improved boost pump chilldown procedures for in-space restart and is not pertinent to the current technology study.

Moore, W. I., Arnold, R. J., "Failure of Apollo Saturn V Liquid Oxygen Loading System," NASA-KSC, Advances in Cryogenic Engineering, Vol. 13, p. 534, August 1967.

The observed conditions are not applicable to low-g fluid transfer.

Novak, J. K. "Cooldown Flow Rate Limits Imposed by Thermal Stresses in Liquid Hydrogen or Nitrogen Pipelines," Univ. of California/Los Alamos, Advances in Cryogenic Engineering, Vol. 15, p. 346, June 1969.

Prediction of thermal stresses during cooldown is important, however, the limited extent of the analysis presented in this paper and the lack of experimental verification of the predictions make its value questionable.

Papell, S. W., "An Instability Effect on Two-Phase Heat Transfer for Subcooled Water Flowing Under Conditions of Zero Gravity," NASA-LeRC, ARS Paper 2548-62, Sept. 1962.

The results presented in this paper are too tentative to be of use in the design of low-g transfer systems.

Platt, G. K., et al, "Feed System Problems of Cryogenic Propellant Rocket Engines," NASA-MSFC, 5th Liquid Propulsion Symposium, November 1963.

This paper is a general discussion of the design of liquid-fueled launch vehicles and does not contribute to the description of the state-of-the-art of low-g fluid transfer.

Rogers, J. D., "Oscillations in Flowing and Heated Subcritical Hydrogen," Univ. of California, Los Alamos, Advances in Cryogenic Engineering, Vol. 13, pp. 223-231, August 1967.

For purposes of the current program this subject is adequately covered in summarized reports such as Streeter and Wylie (1974) and Steward (1968).

Sarlat, I. M., Wilson, T. L., "Surge Pressures in Liquid Transfer Lines," MACDAC, Journal of Basic Engineering, p. 363, September 1962.

Insufficient information is presented to evaluate the usefulness of the material in this paper.

Sleigh, K., "Main Rocket Propellant Feed System Start Transient Analysis and Shutdown Transient Analysis," GD/C, GDC-ERR-1512, June 1970.

This is an IRAD report not generally available.

Suo, M., Griffith, P., "Two Phase Flow in Capillary Tubes," MIT, Technical Report No. 8581-24, Contract No. AF19(604)-7344, March 1963.

The flow regime may be applicable for characterizing the flow in condensors and boilers in low gravity, however, no test data is presented to demonstrate that the correlations do indeed apply to low gravity. Also, the quantitative conditions for capillary slug flow are not specified, thus limiting the usefulness of the data.

Steward, W. G., et al, "Cooldown Transients in Cryogenic Transfer Lines," NBS, Advances in Cryogenic Engineering, Vol. 15, June 1969.

This paper discusses the work performed by Steward (1968) at Colorado State Univ. entitled "Transient Flow of Cryogenic Fluids," which is summarized.

Steward, W. G., et al, "Cooldown Time for Simple Cryogenic Pipelines," NBS, Developments in Mechanics, Vol. 4, p. 1513, 1967.

> This paper discusses the work performed by Steward (1968) at Colorado State Univ. entitled "Transient Flow of Cryogenic Fluids," which is summarized.

Streeter, V. L., Wylie, E. B., "Hydraulic Transients," Univ. of Michigan, McGraw-Hill Book Co., 1967.

> This book is a generalized treatment of unsteady fluid flow. A later article by Streeter and Wylie (1973) dealing specifically with predicting and controlling water-hammer and surge is summarized in lieu of this text.

Urasek, D. C., et al, "Investigation of Two-Phase Hydrogen Flow in Pump Inlet Line," NASA-LeRC, NASA TN D-5258, July 1969.

> The purpose of this study was to evaluate by experiment an analytical method for estimating the vapor-to-mixture-volume ratio for two-phase hydrogen flow in a pump inlet annulus over a range of temperatures and flow rates, and has no direct application to low-g fluid transfer.

Vaage, R. D., et al, "Investigation of Characteristics of Feed System Instabilities," MMC, MCR-72-107, Contract No. NAS8-26266, May 1972.

> These POGO problems are not pertinent to low-g propellant transfer.

Wagner, W. R., et al, "Thermodynamic Improvements in Liquid Hydrogen Turbo-pumps," Rocketdyne, R-8083, Contract No. NAS8-20324, December 1969.

> With respect to low-g heat transfer and in-orbit fluid transfer considerations no new data is presented.

MASS GAUGING

Bupp, F. E., "Development of a Zero-G Gauging System," EAFB, AD-745-566, March 1972.

> The results of this same investigation are contained in Report No. 16740-6003-RU-00, by Bupp (Jan. 1974), a summary of which is included elsewhere.

Collier, R. S., et al, "Mass Quantity Gauging by R. F. Mode Analysis," NBS, NBSIR 73-318, NASA CR-133393, N73-27390, June 1973.

> Mass quantity gauging has been more completely covered by the work done by Bendix in the report "Design, Development and Manufacture of a Breadboard Radio Frequency Mass Gauging System" (1972), which is summarized.

Evans, R. L., Olivier, J. R., "Gas Laws Help Find Propellant Mass at Zero-G," Space/Aeronautics, Vol. 39, June 1963.

This idea has been developed more completely in later work.

Evans, R. L., Olivier, J. R., "Proposal for Determining the Mass of Liquid Propellant Within a Space Vehicle Propellant Tank Subjected to a Zero Gravity Environment," NASA-MSFC, Technical Note D-1571, March 1963.

The principle is presented that propellant mass can be derived from data obtained by monitoring the pressure and temperature of the mass of helium purge gas within an expulsion bladder and the pressure and temperature of the propellant in the tank by applying known gas laws, an idea which has been more completely developed in later works, (See Bliss, 1969, which is summarized).

Fraga, E., Torralbo, A. M., "Feasibility Study for the Development of a Vaporizing Liquid-Fuel Gauge," ESRO, NASA TM X-52876, July 1970.

The gas law method of propellant gauging has been covered in "MOL Propellant Gauging System" by Bliss, which report is summarized.

Garriott, R., Burns, G. A., "Zero-G Propellant Gauging Utilizing Radio Frequency Techniques in a Spherical Resonator," GD/C, San Diego State College, IEEE Transactions on Aerospace, Vol. AS-3, February 1965.

This work has been superseded by more recent extensive investigation and development in this area.

Gronner, A. D., "Methods of Gauging Fluids Under Zero-G Conditions," Simmonds Precision Products, Inc., AIAA Paper No. 65-365, July 1965

This presentation is of a general informative nature only and contributes no significant information to the basic technology.

Loftus, T. A., "Positive Gauging System Feasibility Study," Bendix Corp., NASA-CR-102060, X70-11560, February 1968.

This summary report on RF gauging for propellants under zero-g conditions is outdated by the extensive work done in this area since 1967.

Morrison, R. G., "Zero-G Propellant Gauging of Cryogenics," TRW, NASA TM X-58063, May 1971.

The presentation of three proposed zero-g propellant gauging methods; Resonant Infrasonic Gauging, Nucleonic Gauging and Pulsed Ultra Sonic, is of a sketch/outline nature. These systems have been treated in depth in other papers.

Rod, R.L., "Propellant Gauging and Control, Acoustics Associates, Inc., Rev. Instruments & Control Systems, October 1962.

   This article presents the concept that, in a positive acceleration environment, accurate propellant gauging can be accomplished by utilizing an array of point level sensors in the propellant tank. Since this article was published, further and more detailed work has been accomplished.

Sanmartin, J.R., et al, "Zero-G Gauging Systems," Instituto Nacional De Tecnica Aeroespacial "Esteban Telrados, Contract No. 17/8/4, N73-19452, June 1972.

   R.F. Gauging technology is better covered in the Bendix report: "Design, Development and Manufacture of a Breadboard Radio Frequency Mass Gauging System" which is summarized.

Siegel, B., et al, "Resonant Infrasonic Gauging Apparatus," TRW, NASA-CASE-MSC-11847-1, N70-26814, February 1970.

   A patent disclosure is presented which deals with a refinement in the infrasonic zero-g gauging method. The concept is a minor-refinement only and is of no special significance to low-g fluid transfer technology.

Tate, S.R., "Evaluation and Demonstration of a Propellant Quantity Gauging System for Auxiliary Propulsion Systems," Marquardt Corp., NASA-CR-102759, N70-32145, February 1970.

   An elementary time accumulating system which sums the total fuel consumption of positioning engines based on known engine rates of useage is presented.
   The system is not considered applicable to low-g fluid transfer technology.

Thompson, H.E., et al, "Zero-G Radio Frequency Gauging System for Space Shuttle Propellant Tanks," NASA-MSFC, NASA-TM-X-58063, MF N71-35037, 1971.

   This subject has been completely covered in the report entitled, "Design, Development and Manufacture of a Breadboard Radio Frequency Mass Gauging System," (Anon. 1972), which is summarized.

Wheatley, J.C., Strait, S.F., "An All-Glass Liquid Helium Dewar Employing No Auxiliary Cryogens," U.C. San Diego, La Jolla, American Institute of Physics, Volume 43, Number 6, June 1972.

   The principle advantage of this configuration is that of elimination of distortion of RF Fields (Used in scientific experiments). The idea is of a very specialized nature not applicable to in-orbit fluid transfer.

OTHER INSTRUMENTATION

Anon., "Transducer Applications - A Compilation," NASA, NASA SP-5954(01).

This is a compilation of a wide variety of transducers which have been developed
or improved under various NASA Aerospace programs. No items that could be
related to the zero-g fluid transfer problem are included which are not more
completely presented elsewhere.

Berns, J.A., et al, "Photographic Investigation of Liquid Behavior on Temperature
and Liquid/Vapor Sensors Used in Low-Gravity Environments," NASA-LeRC, NASA
TM X-1438, September 1967.

The results of this work have already been well integrated into the state-of-the-art
design technology for low-g instrumentation.

Brennan, J.A., et al, "An Evaluation of Selected Angular Momentum, Vortex Shedding
and Orifice Cryogenic Flowmeters," NBS, NBS Technical Note 650, March 1974.

This report if supplementary to NBS SP-3084 (Mann, 1974) which is
summarized.

Burgeson, D.A., Richards, R.J., "Selecting Liquid Level Transducers for Cryogenic
Service," NBS Boulder, NBS Report 8784, April 1965.

This paper, contributes nothing to existing technology.

Coney, T.A., Salzman, J.A., "Determination of the Temperature of Gas Mixtures
by Using Laser Raman Scattering, NASA-LeRC, NASA TN D-7126, January 1973.

Deals with the measurement of atmospheric temperature and not applicable to the
present study.

Coon, G.W., "A Capacitive Accelerometer Suitable for Telemetry," NASA-Ames,
NASA TM X-2644, September 1972.

This unit is an excellant design for the intended wind tunnel application, but
no particular application is seen for this type of accelerometer in Low-G Fluid
Transfer Technology.

Corruccini, R.J.,"Temperature Measurements in Cryogenic Engineering," NBS
Advance In Cryogenic Engineering, Vol. 8, August 1962.

Although this paper presents a good review of cryogenic temperature measurement
techniques, no pertinent information of particular use to low "g" space applications
is presented.

Delhaye, J.M., et al, "Void Fraction, Vapor and Liquid Temperatures - Local Measurements in Two-Phase Flow Using a Microthermocouple," France, American Society of Mechanical Engineers 72-HT-13, August 1972.

This paper describes a technique which detects the phase (liquid or vapor) on the hot junction of a micro thermocouple and measures the temperature of each phase in steam-water two phase flow which is a laboratory technique not applicable to space flight operations.

Draper, C.S., et al, "Accelerometer Design and Testing for Zero-G Environment," MIT, DSR Project 52-202, Contract No. AF 04 (694)-305, January 1963.

Information in this paper is of a general type indicating only areas of design requiring research and development rather than presenting solutions.

Hall, R.H., "EMI Test Procedure and Test Report of Bell Aerosystems Zero G Accelerometer," GD/E, EMC-74-002, February 1974.

This is a standard type of a low-g accelerometer and does not in itself add to the overall state-of-the-art.

Hancox, W.T., et al, "Void Determination in Two-Phase Systems Employing Nuetron Transmission," ASME Paper 72-HT-2, August 1962.

The neutron absorption method used in this investigation is already covered in the summarized report "Propellant Quantity Gauging System Under Zero-G" (Anon. 1971).

Johansen, D.G., "Flotation Measurement of Accelerometer Errors Below One Micro-G," Stanford Univ., AFAL-TR-72-45, SUDAAR No. 438, December 1971.

The refinements of micro-g bias error analysis in itself is considered as being of no special significance to the current program.

Joyce, W.B., "Cryogenic Quality Meter," Industrical Nucleonics Corp., N65-14025, CR-60065, November 1964.

Later works report on the implementation of recommendations of this report. Reference: "Nucleonic Measurements of Cryogenic Densities and Qualities," by Scheiwe and Cho., July 1967.

Keller, W.E., "Cryogenic Instrumentation at an Above Liquid Hydrogen Temperature Present and Future," University of California, Advances in Cryogenic Engineering, Vol. 18, August 1972.

This paper is a review of commercial applications of cryogenic technology, present and future; not significant for space consideration.

Lepper, R., "NSL Optical Epihydrogoniometer," Northrop Space Laboratories, American Astronautical Society, Physical and Biological Phenomena Under Zero Gravity Conditions, 2nd Symposium, Los Angeles, Ca., January 1963.

This paper describes a method and a device for measuring the contact angle of a liquid at its interface with a solid, which is not significant with respect to instrumentation required in the operation of in-orbit fluid transfer systems.

Mann, D.B., "Cryogenic Flow-Metering Research at NBS, NBS Boulder, Cryogenics Vol. 11, No. 3, June 1971.

This review is essentially for general information purposes only and does not contribute to the state-of-the-art of low g fluid transfer.

Mann, D.B., "The Flow Measurement of Cryogenic Fluids,," NBS, National Bureau of Standards (U.S.) Special Publication 358 (March 1972) Report of the 56th National Conference on Weights and Measures, July 1971.

This paper is of a general information nature only and does not contribute to the state-of-the-art of low-g fluid transfer.

Miller, C.E., Flynn, T.M., "On the Problems of Measuring Transient Temperature in Cryogenic Fluids," NBS, ISA Transactions, April 1967.

This paper is a study of factors which contribute to the difficulty of accurately measuring transient temperatures in cryogenic fluids and while this information supports the intelligent use of available temperature sensors, it contributes no significant information to the basic technology.

Minzner, R.A., Oberholtzer, J.D., "Space Applications Instrumentation Systems," Electronics Research Center, NASA TM X-2066, May 1972.

This report is a compendium of 158 resumes of instrumentation systems and experiments used or performed during space operations, none of which appear to be related to the problem of Low-G Fluid Behavior or Transfer Technology.

Roder, H.M., "ASRDI Oxygen Technology Survey - Vol. V: Density and Liquid Level Measurement Instrumentation for the Cryogenic Fluids Oxygen Hydrogen and Nitrogen," NBS, NASA SP-3083, 1974.

Data is of a very general nature with no indepth presentation.

Rubin, L.C., "Cryogenic Thermometry: A Review of Recent Progress," MIT Cryogenics Magazine, February 1970.

Although this paper is considered as an excellent outline and is supported by an extensive bibliography, it adds no specifics to the current subject.

Shook, D. F., "Two-Phase Hydrogen Density Measurements by Thermal Neutron Attenuation," NASA-LeRC, NASA TN D-2787, July 1965.

This subject is better covered in the report by J. P. Scheiwe and B. Y. Cho, "Nucleonic Measurements of Cryogenic Densities and Qualities" July 1967, which is summarized.

Sinclair, D. H., Terbeek, H. G., "Cryogenic Temperature Measurement," NASA-LeRC, TM X-52825, July 1970.

This paper does not deal with the problems associated with space environments, space instrumentation or zero-g considerations.

Smetana, J., Wenger, N. C., "Two-Phase Hydrogen Density Measurements Using an Open-Ended Microwave Cavity," LeRC, NASA TN D-6212, March 1971.

Two phase density measurements using the open ended resonant cavity is more completely covered and reported in NASA Technical Note D-6415; "Instrumentation for Liquid Hydrogen Density Measurements using an Open-Ended Microwave Cavity," by Smetana J. and Wenger, N. C., July 1971, which report is summarized.

Stochl, R. J., DeWitt, R. L., "Temperature and Liquid-Level Sensor for Liquid-Hydrogen Pressurization and Expulsion Studies," NASA-LeRC, NASA TN D-4339, February 1968.

This NASA Technical Note describes the design, application and performance of a specially designed thermocouple arrangement for application to measuring ullage gas temperature profiles over LH_2 during pressurization and expulsion studies, an arrangement that is strictly for laboratory application.

Tuman, V. S., Waleh, A., "Cryogenic Gravity Meter," Air Force Cambridge Research Center, AD-754-242, September 1972.

This paper describes a 25 millimicrogal gravity meter which uses superconducting magnets at cryogenic temperature and is not significantly related to zero-g fuel transfer technology.

Wenger, N. C., Smetana, J., "Hydrogen Density Measurements Using an Open-Ended Microwave Cavity," NASA-LeRC, IEEE Transactions on Instrumentation and Measurement, Vol. IM-21, No. 2.

This work was reported by Smetana and Wenger (1971) which is summarized.

Wenger, N. C., Smetana, J., "Liquid-Hydrogen Density Measurements Using an Open-Ended Microwave Cavity," LeRC, NASA TN D-3680, October 1966.

This method has been further investigated and reported in NASA TN D-6415; "Instrumentation for Liquid Hydrogen Density Measurements Using an Open-Ended Microwave Cavity: by Smetana J. and Wenger N. C.,July 1971, which report ised. summarized.

PRESSURE/TEMPERATURE CONTROL SYSTEMS (GENERAL)

Huntley, S. C., "Temperature-Pressure-Time Relations in a Closed Cryogenic Container," NASA-LeRC, NACA TN 4259, February 1958.

> This is very early work in the field which has been superseded by later work.

Stonemetz, R. E., et al, "Long Term Cryogenic Storage System Integration," NASA-MSFC, NASA TM X-64561, October 1970.

> Marshall Space Flight Center's research achievements in the thermal management areas of LH_2 storage in deep space and low orbit environments, including zero-g venting, destratification mixing, hydrogen reliquefaction and solar shields, are outlined in a brief review. Pertinent details are covered in the various contract reports which are reviewed elsewhere.

Wachtler, W.M., Tobolski, J., "Pressure Sensing Control Development for Pressurization and Venting Systems," MCDAC, NASA CR-72748, Contract No. NAS3-13310, March 1971.

> A technology program is discussed in which a hybrid (analog/digital)electronic controller is developed . This is detailed work for a spcific engine feed application not of sufficient general application to in-orbit transfer to warrant summarization

STRATIFICATION/PRESSURIZATION

Abdalla, K.L., et al, "Zero-Gravity Performance of Ullage Control Surface With Liquid Hydrogen While Subjected to Unsymmetrical Radiant Heating," NASA-LeRC, TM X-1001, August 1964.

> Pertinent results of the overall Aerobee program, of which this is a part, are presented by Aydelott (1967). Also this data was included in a pressure rise rate correlation by Blatt (1968).

Abdalla, K.L., et al, "Pressure Rise Characteristics for a Liquid Hydrogen Dewar for Homogeneous, Normal-Gravity Quiescent and Zero-G Tests", NASA, TM X-1134, September 1965.

> This data is included in the report by Aydelott (1967), which is summarized. Pressure rise data here also used in the correlation by Blatt (1968).

Anderson, J.E., et al, "Advanced Pressurization Systems for Cryogenic Propellants," MMC, NASA CR-54467, Contract No. NAS3-2574, January 1967.

> Except for an unsuccessful attempt to use a F_2/H_2 reaction for H_2 tank pressurization, the pertinent work reported here was based on existing state-of-the-art data.

Arnett, R.W., Millhiser, D.R., "A Method for Analyzing Thermal Stratification and Self Pressurization in A Fluid Container," NBS, NBS Project 31505-40-3150451, NBS Report 8777, April 1965.

This work has been refined and extended by Arnett and Voth (1972), which report is reviewed elsewhere.

Arnett, R.W., Voth, R.O., "A Computer Program for the Calculation of Thermal Stratification and Self Pressurization in a Liquid Hydrogen Tank," NBS, NASA CR-2026, May 1972.

This is a detailed stratification program limited to gravity levels where the liquid/vapor interface is flat.

Aydelott, J.C., "Normal Gravity Self-Pressurization of 9-Inch-(23 CM) Diameter Spherical Liquid Hydrogen Tankage," NASA-LeRC, NASA TN D-4171, October 1971.

By itself this work does not add to the state-of-the-art of low-g heat transfer or pressure control. Its relation to low-g work is covered by Aydelott (1967), which report is summarized.

Aydelott, J.C., et al, "Comparison of Pressure Rise in a Hydrogen Dewar for Homogeneous, Normal-Gravity Quiescent, and Zero-Gravity Conditions - Flight 9," NASA-LeRC, NASA TM X-1052, February 1965.

The overall Aerobee flight work is adequately summarized by Aydelott (1967), which report is summarized. Also, this pressure rise data was correlated by Blatt (1968).

Aydelott, J.C., et al., "Comparison of Pressure Rise in a Hydrogen Dewar for Homogeneous, Normal-Gravity Quiescent, and Zero Gravity Conditions - Flight 7," NASA-LeRC, TM-X-1006, September 1964.

Pertinent results of the overall Aerobee and 1-g 9-in. tank tests are adequately summarized by Aydelott (1967). It is noted that the Flight 7 data was used by Blatt (1968) in a pressure rise correlation.

Aydelott, J.C., Spuckler, C.M., "Effect of Size on Normal Gravity Self-Pressurization of Spherical Liquid Hydrogen Tankage," NASA-LeRC, NASA TN D-5196, May 1969.

The data here is strictly 1-g and the evaluation of its usefulness at low-g must await further low-g testing than has been accomplished to date.

Barakat, H.Z., Clark, J.A., "Transient Natural Convection Flows in Closed Containers," Univ. of Michigan, ORA Project 04268, Tech. Rpt. No. 2, Contract No. NAS8-825, August 1965.

The pertinent aspect of this work, an attempt to apply the analysis to actual flight data, is reported by Merte, et al, 1970, which is summarized.

Barnett, D.O., "Liquid Nitrogen Stratification Analysis and Experiments in a Partially Filled, Spherical Container," Northrop Space Laboratories, Advances in Cryogenic Engineering, Vol. 13, pp. 174-187, 1967.

This is 1-g data with no demonstrated application to in-orbit low-g fluid management.

Brady, A.P., et al, "Investigation of the Space Storability of Pressurizing Gases," SRI, NASA-CR-51520, Contract No. NAS7-105, August 1963.

Zero gravity was not really treated in any detail and data which might be pertinent to in-orbit fluid transfer was elementary and/or superseded by more recent work.

Cady, E.C., Kendle, D.W., "Vehicle-Scale Investigation of a Fluorine Jet-Pump Liquid Hydrogen Tank Pressurization Systems," MACDAC, NASA CR-120947, Contract No. NAS3-14381, February 1972.

This report deals with the specific development of a system using Fluorine injected into a hydrogen tank to accomplish controlled combustion and pressurization and is not of general interest to in-orbit transfer.

Chin, J.E., et al, "Analytical and Experimental Study of Stratification and Liquid-Ullage Coupling," Lockheed, 2-06-65-1, August 1965.

The key results of this work culminated in a computer model described in LMSC-A794909-A Vol. IV (Anon.), which is summarized.

Clark, J.A., "A Review of Pressurization, Stratification, and Interfacial Phenomena," Univ. of Michigan, Advances in Cryogenic Engineering, Vol. 10, August 1964.

This is a good review of the work accomplished up to 1964, however, significant work has been accomplished since and the only data presented here are for 1-g.

Clark, J.A., Barakat, H.Z., "Transient, Laminar, Free-Convection Heat and Mass Transfer in Closed, Partially Filled, Liquid Containers," Univ. of Michigan, ORA Project 04268, Contract No. NAS8-825, January 1964.

The pertinent aspect of this work, an attempt to apply the analysis to actual flight data, is reported by Merte, et al, 1970, which is summarized.

Danilowicz, R.L., "Computer Code for Calculating Temperature Profiles in a Propellant Tank," NASA-LeRC, NASA TM X-1556, April 1968.

Only applicable to 1-g and nuclear heating with pressure rise not included.

DeWitt, R.L., et al, "Experimental Evaluations of Pressurant Gas Injectors during the Pressurized Discharge of Liquid Hydrogen," NASA-LeRC, TN D-3458, June 1966.

1 -g testing. Pertinent aspects of this work are presented in NASA TMX-52573, Stochl and DeWitt, 1969, which is reviewed elsewhere.

Epstein, M., Prediction of Liquid Hydrogen and Oxygen Pressurant Requirements," Rocketdyne, Advances in Cryogenic Engineering, Vol. 10, pp. 303-307, August 1964.

This work has been extended by Epstein and Anderson, 1967, which is summarized.

Epstein, M., Georgius, H.K., "A Generalized Propellant Tank-Pressurization Analysis," Rocketdyne, Advances in Cryogenic Engineering, Vol. 10, pp. 290-302, August 1964.

The current state-of-the-art of the computer program described here is represented by later work; e.g. the summarized report by Bradshaw, et al, 1970, (GDC-DDB-70-003) and the report by Nein and Thompson, 1966, (TN D-3177).

Flaherty, W.J., et al, Pressurization Systems Design Guide," Aerojet General, NASA CR-80316, Contract No. NAS7-169, July 1966.

This is a useful compilation of design information associated with the various aspects of different types of pressurization systems, however, it is based on existing technology data and the state-of-the-art in 1966.

Gorman, D.N., et al, "Lightweight Pressurization System for the Apollo Service Propulsion System," MMC , NASA CR-65837, Contract No. NAS9-3521, January 1967.

A cryogenic helium storage system was developed and tested. This work deals with detailed pressurization system hardware, which is beyond the scope of the current technology study.

Heaton, T.R., et al, "Development and Demonstration of Main Tank Injection (MTI) Pressurization System, Final Report," MMC, RTD-TDR-63-1123, Contract No. AF 04 (611)-8198, December 1973.

The use of one propellant to react with another to accomplish tank pressurization is primarily applicable to engine feed systems and not of general interest to in-orbit fluid transfer.

Huntley, S.C., et al, "Wall and Bottom Heating of Liquid Hydrogen in a Propellant Tank," NASA-LeRC, NASA TN D-3256, February 1966.

The test data was obtained at 1-g and no attempt was made to apply the results to low-g.

Keller, W.F., "Design, Fabrication and Test of a Breadboard Hybrid Pressurization System," Northrop, NOR 69-129, Contract No. NAS7-714, May 1970.

A system is developed to generate hot nitrogen suitable for direct contact pressurization of both fuels and oxidizers of typical earth and space storable propellants. This work deals with detailed pressurization system hardware, which is beyond the scope of the current technology study.

Kendle, D.W., "Tank Pressurization," MACDAC, Proceedings of Low-G Seminar at MACAC, May 1969.

This is just a brief survey of the state-of-the-art, which is adequately covered by individual works which are summarized.

Knoll, R.H., et al, "Weightlessness Experiments With Liquid Hydrogen in Aerobee Sounding Rockets; Uniform Radiant Heat Addition - Flight 1," NASA-LeRC, NASA TM X-484, June 1962.

Results of the overall Aerobee flight program are satisfactorily summarized by Aydelott (1967), which report is summarized.

Liebenberg, D.H., Edeskuty, F.J., "Pressurization Analysis of a Large-Scale Liquid-Hydrogen Dewar," Univ. of California, International Advances in Cryogenic Engineering, Vol. 10, 1964.

The test data was obtained at 1-g and no attempt was made to apply the results to low-g.

Lovrich, T.M., et al,"Development of Thermal Stratification and Destratification Scaling Concepts - Final Report," MACDAC, MDC G4753, Contract No. NAS8-23747, July 1973.

Even though extensive testing was accomplished at 1-g, using Freon 113 in different size tanks, the results were only of a general nature and not significant to in-orbit fluid transfer, as compared to other work in this field. Satisfactory pressure scaling was only demonstrated for the simple case of liquid heating where the tank fluid would be essentially mixed.

McArdle, J.G., et al, "Weightlessness Experiments With Liquid Hydrogen in Aerobee Sounding Rockets; Uniform Radiant Heat Addition - Flight 2," NASA-LeRC NASA TM X-718, December 1962.

Results of the overall Aerobee flight program are satisfactorily summarized by Aydelott (1967), which report is summarized.

Moses, R.A., Gluck, D.F., "Cryogenic Thermal Stratification and Interfacial Phenomena for Heated Tanks During Prolonged Orbital Flight," NAR, Advances in Cryogenic Engineering, Vol. 13, pp. 81-91, August 1972.

Even though the effects of low-g are discussed and an acceleration term exists in the equations, this analysis is similar to those typically used for 1-g and no low-g test data are presented for verification.

Nunamaker, R.R., et al, "Weightlessness Experiments With Liquid Hydrogen in Aerobee Sounding Rockets; Uniform Radiant Heat Addition - Flight 3," NASA-LeRC, NASA TM X-872, December 1963.

Pertinent results of the overall Aerobee flight program are presented by Aydelott (1967), which report is summarized. Also, pressure rise data have been correlated by Blatt (1968).

Olsen, W.A., "Experimental and Analytical Investigation of Interfacial Heat and Mass Transfer in a Pressurized Tank Containing Liquid Hydrogen," NASA-LeRC, TN D-3219, March 1966.

This is a good, thorough treatment of interfacial heat and mass transfer, however, testing was only accomplished at 1-g and the basic results have been incorporated into later works which are summarized.

Pennington, K., Jr., "The Aerobee Zero-Gravity Test Program - A Summary of Results, GD/C, BTC63-001, Contract No. NAS3-3232, April 1963.

Pertinent results of the overall Aerobee flight program are presented by Aydelott (1967), which report is summarized.

Poth, L.J., Van Hook, J.R., "Thermal Stratification of Cryogens Stored in a Low-Gravity Environment," GD/FW, Institute of Environmental Science Proceedings, Vol. 1, April 1971.

Pertinent aspects of this work are reported under contracts NAS8-24882 and NAS8-20330, Poth, et al, 1968 and 1970 and in AIAA Paper No. 71-646, Poth and Van Hook, 1971, which reports are reviewed elsewhere.

Regetz, J.D., "Weightlessness Experiments With Hydrogen in Aerobee Sounding Rockets; Nonuniform Radiant Heat Addition - Flight 4," NASA-LeRC,TM X-873, February 1964.

See the summarized report by Aydelott (1967) for pertinent results of the overall Aerobee program. Also, pressure rise data have been correlated by Blatt (1968).

Robbins, J.H., Rogers, A.C., Jr., "An Analysis on Predicting Thermal Stratification in Liquid Hydrogen," NAR, AIAA Paper No. 64-426, July 1964.

This is one-g data without particular application to in-orbit fluid management.

Roudebush, W.H., "An Analysis of the Problem of Tank Pressurization During Outflow," NASA-LeRC, TN D-2585, January 1965.

The current state-of-the-art of this work is represented by the summarized work of Stochl, 1970 (TN D-7019).

Roudebush, W.H., Mandell, D.A., "Analytical Investigation of Some Important Parameters in the Pressurized Liquid Hydrogen Tank Outflow Problem," NASA-LeRC, TM X-52074, 1964.

This work is reported in greater detail in TN D-2585 by Roudebush, 1965.

Sherman, A.L., "Parameterization Study of the S-IVB Liquid Oxygen Tank Pressurization System," MACDAC, Joint Army-Navy Force Liquid Propulsion Meeting, 12th, Publication No. 201-Vol. 1, pp. 347-363.

General discussions and trade-offs presented here are based on existing technology data.

Stochl, R.J., et al, "Gaseous-Helium Requirements for the Discharge of Liquid Hydrogen from a 1.52-Meter-(5-Ft-) Diameter Spherical Tank," NASA-LeRC, NASA TN D-5621, January 1970.

1-g testing. This work has been expanded by testing in a 13-ft-dia. tank as reported in NASA TN D-7019, Stochl, et al, 1970, which is summarized.

Stochl, R.J., et al, "Gaseous-Hydrogen Pressurant Requirements for the Discharge of Liquid Hydrogen from a 3.96-Meter-(13-Ft-) Diameter Spherical Tank,: NASA-LeRC, TN D-5387, August 1969.

1-g testing. Pertinent aspects of this work are summarized in NASA TM X-52573, Stochl and DeWitt, 1969, which is summarized.

Stochl, R.J., et al, "Gaseous-Hydrogen Requirements for the Discharge of Liquid Hydrogen from a 1.52-Meter- (5 Ft) Diameter Spherical Tank," NASA-LeRC, TN D-5336, August 1969.

1-g testing. Pertinent aspects of this work are summarized in NASA TM X-52573, Stochl and DeWitt, 1969, which is summarized.

Stochl, R.J., DeWitt, R.L., "Pressurant Gas Requirements for the Pressurized Discharge of Liquid Hydrogen from Propellant Tanks," NASA-LeRC, AIAA Paper No. 69-526, June 1969.

This is the same as NASA TM X-52573 by Stochl and DeWitt, 1969, which is summarized.

Tatom, J.W., "Analysis of Thermal Stratification of Liquid Hydrogen in Rocket Propellant Tanks," Lockheed, Advances in Cryogenic Engineering, Vol. 9, pp. 265-272, August 1963.

This is 1-g data without any correlation to low-g. For additional work by the author on this subject, See Tatom, 1966, which report is reviewed below.

Tatom, J.W., "Transient Free Convection in a Closed Container with Heating at the Bottom and at the Sides," Georgia Institute of Technology, Ph. D. Thesis, May 1966.

This is one of a fairly large number of reports containing 1-g stratification data, the low-g usefulness of which must await evaluation through low-g testing.

Tatom, J.W., et al, "Analysis of Thermal Stratification of Liquid Hydrogen in Rocket Propellant Tanks," Lockheed, ER-6759, 1963.

This report is identical to a paper presented by the authors at the 1963 Cryogenic Engineering Conference, which paper is reviewed above.

Thompson, J.F., Nein, M.E., "Prediction of Propellant Tank Pressurization Requirements by Dimensional Analysis, NASA-MSFC, June 1966.

The summarized work of Epstein and Anderson, 1967 is taken to be representative of the state-of-the-art of pressurant predictions using relatively simple equations.

Walburn, A.B., et al, "Development of Analytical Methods for Predicting Residual Cryogenic Propellant Behavior in Orbital Vehicles," GD/C, GDC-DDB67-003, Contract No. NAS8-20165, November 1967.

Computer programs were developed to predict internal tank thermodynamics and forces on a vehicle generated by venting. The current state-of-the-art of the thermodynamics model is represented by work presented in the summarized report by Bradshaw, et al, 1970 (GDC-DDB-70-003).

Wapato, P.G., et al, "Study of External Pressurization Systems for Cryogenic Storage Systems," AiResearch, Contract No. NAS9-10453, September 1971.

The design of external pressurization systems for supercritical cryogenic storage systems is investigated. Just one approach is presented which is mostly concerned with hardware details not peculiar to low-g operation

Wengar, R.K., "Pressurization Collapse in Cryogenic Propellant Tankage Due to Sub-Surface Vapor Bubbles," MACDAC, Proceedings at Low-G Seminar at MACAC, May 1969.

Some H_2 tank data are presented from S-IVB flights 501 and 502, however, the data and its evaluation are not sufficient to draw meaningful conclusions other than that "more experimentation under carefully controlled conditions is necessary before accurate prediction of bubble-induced collapse is possible."

Winstead, T.W., "Propellant Thermal Stratification," NASA-MSFC, NASA TM X-64561, October 1970.

A semiemperical prediction method was developed for high-gravity environments for application to the LH_2 tanks of the Saturn booster stages. Low-g was not treated in any detail.

VENT SYSTEMS

Boraas, S., et al, "Evaluation of Propellant Containment and Venting Devices for Zero Gravity Applications," Bell Aerosystems, AFRPL-TR-64-118, Contract No. AF 04 (611)-9901, June 1965.

The critical phase of this work was a low-g test of the most promising system selected here, which is covered by Bovenkerk (1969), which is summarized.

Bullard, B. R., "Wall Mounted Heat Exchanger Characterization,", LMSC, LMSC/D347802, Contract No. NAS3-16769, July 1973.

This program is concerned with the design and evaluation of a heat exchanger vent system for tank pressure control at low-g. This is only a quarterly report. It is expected that the final report will be out sometime in November or December 1974, under CR-134536.

Cady, E.C., "A Comparison of Low-G Thermodynamic Venting Systems," MACDAC, MACDAC-63174, April 1969.

The work reported here is essentially the same as that reported by the author in the May 1969 Low-G Seminar at MACDAC, which report is reviewed elsewhere and which is more readily available than the current work.

Cady, E.C., "Thermodynamic Vapor-Liquid Separator," MACDAC, Proceedings of Low-G Seminar at Douglas, May 1969.

Mostly just a review of existing data. The only new item is the use of electro convection to replace the mechanical pump in a bulk heat exchanger system, the performance of which is only speculation. The potential success of such a system would be allied with that of dielectrophoretic orientation, the technology of which is reviewed elsewhere.

Carter, W.J., Jr., "A Literature Survey and Analysis of Mists 1-10 μ Size and Moisture Separators," AEC, MSAR 70-10, Contract No. AT (45-1)-2145), January 1970.

An interesting survey and a good bibliography are presented, however, this work by itself does not advance the state-of-the-art of liquid/vapor separation as it applies to low-g venting systems or in-orbit fluid transfer.

Dowty, E.L., Murphy, D.W., "Heat Exchanger Design for Cryogenic Propellant Tanks," MMC, Advances in Cryogenic Engineering, Vol. 13, August 1967.

It is noted that energy balances and testing were associated with an exchanger attached only in the ullage region of a tank operating at one-g and would not have the same characteristics as one required to operate at low-g with all liquid orientations. More significant work has been accomplished since; e.g., Page and Tegart, 1969 and Bullard, et al, 1973.

Fester, D.A., et al, "Liquid Fluorine No-Vent Loading Studies," MMC, Journal Spacecraft, Vol. 7, No. 2, February 1970.

This is a specialized study with limited application. The general concept of non-vented oxidizer tanks is covered by the report by Murphy and Rose, 1968 which is reviewed elsewhere.

Hill, D.E., Salvinsky, R.J., "A Thermodynamic System for Zero-G Venting, Storage, and Transfer of Cryogenic Propellants," TRW, Journal Spacecraft, Vol. 4, No. 7, July 1967.

The significant aspects of this program are presented in greater detail by Salvinski, et al, 1965, which report is reviewed elsewhere.

Kavanagh, H.M., Rice, P.L., "Development of Subcritical Oxygen and Hydrogen Storage and Supply Systems - Final Report, " AiResearch, SS-3169, Contract No. NAS9-1065, September 1964.

This is only the first phase of a program which is covered in its entirety by Allgeier, 1968, which report is summarized.

Kloepfer, W.W., et al, "Liquid Hydrogen Heat Transfer," GD/C, Report No. 55D388, August 1960.

Tests were run in 1-g using LH_2 to demonstrate the feasibility of the thermodynamic heat exchanger low-g vent concept for use in the Centaur however, this is very early and only preliminary work on a subject which is covered more completely in later reports.

Merino, F., et al, "Investigations of the Centaur Vent Tube (Zero-g Vent Device)," GD/C Ay62-0012, Contract No. AF18(600)-1775, July 1962.

The center vent tube concept is based on locating the vent inlet at a point in the tank where vapor is expected to be under zero-g conditions with the important factor being liquid/vapor interface shape and non-wetting of the vent tube, which is covered more thoroughly in the Low-G Fluid Behavior volume.

Murphy, D.W., et al, "Vent Free Fluorine Feed System," MMC, AFRPL-TR-67-323 (Volume I), Contract No. F04611-67-C-0044, March 1968.

The significant test phase of this work is reported by Page and Tegart, 1969, which is summarized. Also the current report is confidential.

Murphy, D.W., Rose, L.J., "Vent-Free Fluorine Feed System," MMC, AFRPL-TR-67-323 (Volume II), Contract No. F04611-67-C-0044, June 1968.

The significant test phase of this work is reported by Page and Tegart, 1969, which summarized.

O'Neal, A.P., et al, "Saturn V/S-IVB Stage Orbital Vent System Backup Study," MACDAC, SM-47202, Contract No. NAS7-101, May 1965.

Technology details are not presented and the vent systems discussed here are covered in more detail in other work, e.g. Mitchell, et al, (1966), which report is summarized.

Polk, R.L., "Subcritical Liquid Oxygen Storage and Conversion System for Omnigravic Operation," AiResearch, AMRL-TDR-62-143, Contract No. AF 33 (616)-7153, December 1962.

More recent and comprehensive work in this area is presented by Allgeier (1968), which is summarized.

Rhoton, R.L., "Cryogenic Storage and Expulsion Means," MACDAC, U.S. Patent No. 3,699,696, October 1972.

This patent describes a typical storage system with insulation, throttling valve, and wall heat exchanger. See Page & Tegart (1969) and Allgeier (1968) for more detailed information on this subject area.

Rosin, A.D., Pope, A.M., "Zero Gravity Separator," NASA, U.S. Patent 3,257,780, June 1966.

> Two different versions of dynamic liquid/vapor separators are described for the low-g vent application. These particular units were built and tested under a GD/C contracted program which is covered by Mitchell, et al, (1966), which report is .

Salvinski, R., et al, "Advanced Valve Technology for Spacecraft Engines - Final Report," TRW, 8651-6042-SU-000, Contract No. NAS7-107, August 1965.

> Work pertinent to the current program was conducted in the area of zero-g venting where a wall heat exchanger vent system was fabricated and tested using both LN_2 and LH_2, however, this is very early work on the subject and has been superseded by later work; e.g., Page and Tegart, 1969 and Bullard, et al, 1973.

Stark, J.A., Blatt, M.H., "Test Results of a Zero-Gravity Cryogenic Phase Separator," GD/C, Paper F-5, Advances in Cryogenic Engineering, 1968.

> This work is reported in greater detail in Report GDC-DDB67-006 by the authors, October 1966 which is summarized.

Stark, J.A., Mitchell, R.C., "Study of Vapor/Liquid Separators for Venting Cryogenic Propellant Tanks in Space," GD/C, Conference on Long-Term Cryo-Propellant Storage in Space held at the MSFC, October 1966.

> This work is covered in more detail by Mitchell, et al, 1966, which report is summarized.

Sterbentz, W.H., et al, "Liquid Propellant Thermal Conditioning System - Interim Report," LMSC, LMSC-A839783, NASA CR-72113, Contract No. NAS3-7942, April 1967.

> This is an interim report; the significant phase of the work (testing and data analysis) is covered in the final report (Sterbentz, et al, 1968), which report is summarized.

Ward, W.D., "Vapor-Liquid Separator," NASA, Patent No. 3,397,512, December 1966.

> Without test and further analysis the usefulness of this system, as compared to similar systems, is mere speculation.

Warren, R.P., Anderson, J.W., "A System for Venting a Propellant Tank in the Absence of Gravity,"LMSC, Advances in Cryogenic Engineering, Vol. 12, pp. 63-71, June 1966.

Not enough data was presented to fully evaluate performance. Also, later and more advanced work on the subject is presented by Page and Tegart, 1969, and Bullard, et al, 1973.

Zara, E.A., "Flight Test of a Subcritical Cryogenic Storage Vessel," AFFDL, AFFDL-TR-68-46, June 1966.

This system is basically a gas supplier, with external heating available for liquid vaporization, rather than a low-g venting system.

FLUID MIXING

Booth, F.W., Bruce, R.A., "Zero Gravity Liquid Mixer," NASA, Patent Application (NASA-Case-LAR-p0195-1), November 1971.

Mixing of two different liquids as proposed here is not pertinent to the current in-orbit-fluid transfer program.

Bradshaw, R.D., Stark, J.A., "Cryogenic Propellant Conditioning With Jet Mixing," GD/C, Joint AIChE-IIQPR Meeting, Tampa Florida, May 1968.

This paper was never published and would therefore not be generally available. For some of the basic test results see Stark and Blatt, 1967, which report is summarized.

Catton, I., "Feasibility of Rotational Destratification of Space-Stored Liquid Cryogens," MACDAC, DAC-63140, May 1969.

Even though this brief analysis does indicate the feasibility of providing some convective heat transfer by tank rotation, the work is only analytical and not extensive enough or with sufficient quantitative data to be useful in the current program.

Fendell, F.E., "Heat Transfer to Rotating Cryogenic Fuel Tanks in Orbit," TRW, AIAA Paper No. 66-432, June 1966.

This is only preliminary work on the problem, without experimental verification. For later work on this subject, see Catton, 1969, which is reviewed elsewhere.

Fossett, H., "The Action of Free Jets in the Mixing of Fluids," Associated Ethyl Co., Trans. Instn. Chem. Engrs., Vol. 29, 1951.

This is a good basic jet mixing report, however, no attempt was made to relate the work to low-g. For work more directly applicable to in-orbit fluid management see Berenyi, et al, 1968 and Poth, et al, 1968, which reports are summarized.

Holmes, L.A., Krane, R.J., "An Experimental Study of the Effects of Low Bond Number Sloshing on Thermal Stratification," MACDAC, DAC-63140, May 1969.

Even though test data using water sloshing in a small Plexiglas cylinder at 1-g were obtained, the usefulness is only qualitative and limited in scope since an in-depth analysis was not made and the dimensionless temperature moment used to correlate the data was not even quantitatively defined. The basic conclusion was that stable nonplanar sloshing provided greater destratification than unstable nonplanar or stable planar sloshing.

Krane, R.J., Holmes, L.A., "Experimental Study of the Effects of Low Bond Number Sloshing on Thermal Stratification," MACDAC, AIAA Journal, Vol. 11, No. 9, September 1973.

This work is covered more thoroughly by Holmes and Krane (1969), which report is reviewed above.

Morgan, R.W., et al, "Design and Development Liquid Hydrogen Mixer Unit," AiResearch, NASA CR-120963, Contract No. NAS8-11208.

The feasibility of using a small (0.5 to 2.5w) brushless dc motor to drive a cryogenic LH_2 mixer was demonstrated. Increased efficiency over an ac motor was also indicated, however, some electronic failures occurred. Further details of this work are associated with component fabrication beyond the scope of the current program.

Neff, B.D., "Investigation of Stratification Reduction Techniques," MMC, Proceedings of the Conference on Propellant Tank Pressurication & Stratification at MSFC, January 1965.

It was significant that bubble pumps did not effect a reduction in pressure rise rate, however, this report is not generally available.

Pal, D., "A Fluidic System for Mixing Two Fluids - Final Study," Naval Civil Engineering Laboratory, AD-774 486, NCEL-TN-1314, December 1973.

This study is concerned with controlling the mixture ratio of two or more fluids such as hot and cold water coming together in two or more streams and is not applicable to the current program.

Poth, L.J., et al, "A Study of Cryogenic Propellant Stratification Reduction Techniques Annual Report," GD/FW, FZA-419-1, Vol. I and Vol. II, Contract No. NAS8-20330, September 1957.

This work has been amplified and expanded from that presented here; Reference, Poth, et al, 1968, which is summarized.

Poth, L.J., Van Hook, J.R., "Control of the Thermodynamic State of Space-Stored Cryogens by Jet Mixing," GD/FW, Journal Spacecraft, Vol. 9, No. 5, May 1972.

> This is the same work as reported under contracts NAS8-24882 NAS8-20330, Poth, et al, 1968 and 1970 and in AIAA Paper No. 71-646, Poth and Van Hook, 1971,

Poth, L.J., Van Hook, J.R., "Control of the Thermodynamic State of Space-Stored Cryogenic Fluids by Jet Mixing," GD/FW, AIAA Paper No. 71-646, June 1971.

> This work is covered in greater detail in contract reports, e.g., Van Hook and Poth, 1970, which report is summarized.

Schoenhals, R.J., et al, "Use of Multiple Outlets for Reducing the Stratification Induced Propellant Supply Temperature Rise," Purdue Univ., A69-42830, AAS Paper 69-395, Contract No. NAS8-20222, June 1969.

> Taking fluid from different parts of a tank to obtain a mixed fluid flow to an eingine is proposed along with some test data demonstrating the idea. This is not of primary significance to in-orbit fluid supply.

Thomas, F.W., Holmes, L.A., "A Visual Study of Propellant Destratification," MACDAC, NASA N71-13108, Douglas Low-G Seminar, May 1969.

> No quantitative data are presented and the qualitative data presented are not significant as compared to other work in this field; e.g., Poth, et al, 1968, which report is summarized.

REFRIGERATION & RELIQUEFACTION

Benning, M.A., et al, "Development of a Practical Thermodynamic Cycle for Space-Borne Hydrogen Reliquefier," Air Products, Advances in Cryogenic Engineering, Vol. 14, p. 378, August 1968.

> This is the same work which is reported in greater detail by the authors in the contract NAS8-21203, 1972 final report.

Benning, M.A., et al, "Handbook for Hydrogen Reliquefier," Air Products, NAS Contract No. NAS8-21203, October 1972.

> General system and hardware characteristics, along with test results are adequately covered by the summary technical report under this contract (same author and date), which is summarized.

Breckenridge, R.W., Jr., "Spaceborne Refrigeration Systems," A.D. Little, "Cryogenics and Infrared Detection Systems, A Technical Colloquium," Frankfurt Am Main, West Germany, April 1969.

More extensive information of this type and more oriented to the current program is presented by Jensen, et al, 1971, which is summarized.

Gibson, L.A., et al, "Extraterrestrial Reliquefaction of Cryogenic Propellants," Marquardt Corp., Report 6099, Contract No. NAS8-5298, December 1965.

This was initial work on the subject which has culminated in the fabrication and test of a partial H_2 reliquefier as reported by Benning, et al, 1972, which report is summarized.

Neal, L.G., et al, "Study of a Heat Rejection System Using Capillary Pumping," TRW, NASA CR-1895, Contract No. NAS3-12976, November 1971.

Results of an analytical study investigating the application of capillary pumping to the heat rejection loop of an advanced Rankine Cycle power conversion system are presented, however, the work was only analytical and Rankine Cycle power systems in themselves are not of interest to the current program.

Rose, A., et al, "Hydrogen Reliquefaction in Earth Orbit," Marquardt Corp., Advances in Cryogenic Engineering, Vol. 12, p. 37, June 1966.

This is the same work as reported by Gibson, et al, 1965, in the contract NAS8-5298 final report which is reviewed elsewhere.

Sedgwick, T.A., (Marquardt Corp.), Middleton, R.L., (NASA-MSFC), Advances in Cryogenic Engineering, Vol. 11, p. 241, August 1965.

This is the same work as reported by Gibson, et al, 1965, in the contract NAS8-5298 final report which is reviewed elsewhere.

Strobridge, T.R., "Cryogens Refrigerators - An Updated Survey," NBS, NBS Technical Note 655, June 1974.

Data of this type more specificaly oriented to the current space application is presented by Jensen, et al, 1971,which report is summarized.

INTERFACE CONTROL & LIQUID ACQUISITION (GENERAL)

Barcatta, F.A., et al, "Zero G Propellant Feed Systems for Cesium Ion Rocket Engines," AIAA Electric Propulsion, AIAA 63027, March 1963.

Data is not presented in a useful form. See Trump, et al, 1966, for more recent work on surface tension device storage means for providing liquid to the vaporizer.

Bhuta, P.G., Johnson, R.L., "Liquid Vapor Separator and Cryogenic Liquid Converter," TRW, U.S. Patent No. 3,492,793, February 1970.

> The development of this concept is covered more thoroughly by Paynter and Page, 1973, which report is summarized.

Bitten, J., "Liquid Oxygen Converter," WADD, WADD-60-669, ARF 3164-12, Contract No. AF 33(616)-6756, January 1961.

> Other more comprehensive studies of capillary force feed systems are summarized elsewhere.

Bitten, J.F., "Liquid Oxygen Converter," IIT Research Institute, Chemical Engineering Progress Symposium Series, 1965.

> The system uses magnetic forces as well as capillary force to deliver LO_2. Insufficient design information is presented to aid the fluid transfer system designer.

Castle, J.N., "Surface Tension and Dielectrophoresis," MACDAC, Lecture 19 in Proceedings of Low-G Seminar, Blackmon J.B., May 1969.

> The report is a brief overview with information presented obtainable from other sources that have been summarized, e.g., Debrock,1970.

Chipchak, D., et al, "Development of Expulsion and Orientation Systems for Advanced Liquid Rocket Propulsion Systems,"Bell Aerosystems, RTD-TDR-63-1048, Contract No. AF04(611)-8200, July 1963.

> The two techniques selected for detailed analysis have been subjected to considerable development since this program was completed.

Driscoll, D.G., "Cryogenic Tankage for Space Flight Applications," Linde, Advances in Cryogenic Engineering, Vol. 5, Paper B3, 1959.

> This is only a general discussion of designs of tanks for space storage of cryogenic liquids and adds nothing to the current state-of-the-art of liquid expulsion techniques.

Green, R.L., "Advanced Techniques for Determining Long Term Compatibility of Materials with Propellant," Boeing, Fluids and Materials Compatibility Symposium, CPIA Publication 240, July 1973.

> The material in this paper, as presented, is not directly pertinent to the low-g transfer study.

Holcomb, L.B., Womack, J.R., "Design of a Mercury Propellant Storage and Distribution Assembly," JPL, AIAA 73-1119, November 1973.

> This paper discusses considerations which must be taken into account in designing a positive expulsion system. It does not, however, add to the state-of-the-art.

Krivetsky, A., et al, "Research on Zero-Gravity Expulsion Techniques," Bell Aerosystems, 7129-933003, NASr-44, March 1962.

> This program is an extensive review of all propellant acquisition and expulsion systems to 1962. Recent developments have made it obsolete.

Murray, R.W., et al, "Engineering Aspects of Zero Gravity-Personal Hygiene and Waste Management Systems, GD, AIAA Paper No. 71-865, August 1971.

> Only general not-in-depth discussions are presented. For better data on this subject, see Rosener, et al, 1971, under "other acquisition systems."

Park, L.T., et al, "Titan Transtage Spacecraft Propulsion System," MMC, AIAA Paper No. 73-1210, F-152, November 1973.

> Primarily deals with overall system description with no real details given. Does not add to the state-of-the-art.

Parmley, R.T., "In Space Propellant Orientation and Venting Experiments," LMSC, AFRPL-TR-68-54, April 1968.

> The result of this program was an operational piece of hardware delivered to AFRPL. The Phase I portion of this study (Parmley, 1966), summarized elsewhere, presents the selection criteria and preliminary design information. The Phase II report presenting information on experiment definition and fabrication does not provide fluid transfer system design information.

Paynter, H.L., "Investigation of Space Storable Propellant Acquisition Devices," MMC, MCR-70-171, Contract No. NAS7-754, October 1970.

> Considerable improvement of surface tension devices has been made since this study was completed.

Pohl, H.O., Kendrick, D., "Space Shuttle Auxiliary Propulsion System," NASA-JSC, JANNAF Combined Propulsion Meeting, November 1971.

> This paper provides a parametric comparison of the weights of three reaction control systems with general comments about relative advantages and development status of acquisition devices, however, the discussion of the various acquisition devices is too general in nature to be of use in the present study.

Porter, R.N., Stanford, H.B., "Propellant Expulsion in Unmanned Spacecraft," JPL, Paper 868B, April 1964.

This work has been superseded by more recent investigations.

Prescott, W.T., "Liquid Gas Separation System," NASA, U.S. Patent No. 3,224,173, December 1964.

The basic application is for environmental control systems and similar devices have been built and tested under more current work reviewed elsewhere, e.g. Rosener, et al, 1974, under "other acquisition systems."

Stein, E.E., Van Splinter, P.A., "Propellant Expulsion Techniques," AFRPL, International Conference on Space Engineering, 2nd, Venice Italy, (A69-31734), May 1969.

This discussion is very general with no significant data presented.

Williams, L.O., "Hydrazine Purity Influence on Construction Material Compatibility," MMC, AIAA Paper No. 73-1264, November 1973.

The material presented in this paper is not directly pertinent to the low-g propellant transfer study.

Yankura, G., "JPL Long Term Propellant-Material Compatibility Program," AFRPL, Fluids and Materials Symposium, CPIA Publication 240, July 1973

The material in this paper, as presented, is not directly pertinent to the low-g transfer study.

Ziegler, L., "Water and Waste Management Subsystem Design for a Space Station Prototype," Hamilton Standard, ASME Paper 72-ENAv-8, August 1972.

Liquid-gas separation by vortex and surface tension phenomena is discussed, however, insufficient details are given to be of use to the current program.

CAPILLARY ACQUISITION

Balzer, D.L., "Advanced Propellant Management System for Spacecraft Propulsion Systems Summary Volume," MMC, MCR-69-437, Contract No. NAS9-8939, September 1969.

This report is a synopsis of two other volumes of the study that were both individually summarized.

Balzer, D.L., Lake, R.J., Jr., "A Comparison of Neutral Buoyancy and Free Fall for Liquid Propellant," RCA Astro-Electronics Division, AIAA Paper No. 72-1041, November 1972.

The report doesn't add to capillary acquisition knowledge. For a critique of neutral buoyancy see De Brock, 1973.

Balzer, D.L., Lake R.J., "Low G Simulation Testing of Propellant Systems Using Neutral Buoyancy," RCA, NASA SP-298, May 1972.

The report is similar to AIAA Paper No. 72-1041, Balzer, D.L., and Lake, R.J., Jr., 1972.

Barber, H.W., Lavi, R., "Negative G Drone Aircraft Surface Tension Fuel System," Northrop Corp., AIAA Paper No. 70-910, July 1970.

No design data was presented.

Bhuta, P.G., Johnson, R.L., "Zero-G Cryogenic Liquid Expulsion Device," TRW AIAA Aerospace Conference, p.85, May 1968.

This report discusses the double liner concept for venting and outflow with cryogens. Test data presented is difficult to interpret. Reports by Paynter, and Page, 1973, that are summarized, adequately treat this subject.

Blatt, M.H., et al, "Low Gravity Propellant Control Using Capillary Devices in Large Scale Cryogenic Vehicles - Related IRAD Studies," GD/C, GDC DDB70-009, Contract No. NAS8-21465, August 1970.

The report describes Convair work on screen flow testing, settling, residual analysis, bubble motion and surface tension properties. However, screen flow pressure drop is adequately covered in Cady, 1973. Important information presented on draining is presented in Satterlee and Hollister, 1967. Settling work merely consolidates drop tower testing reported by NASA/LeRC and work on bubble motion, agglomeration, and vaporization is significant but is not directly usable without the computer program which is proprietary.

Bovenkerk, P.E., Captain, USAF, "Zero-Gravity Test of an Advanced Surface-Tension Propellant Orientation and Ullage Vapor Venting Device," AFRPL, AFRPL-TR-69-119, June 1969.

Very brief discussion makes evaluation of this work difficult for propellant orientation. Referenced reports giving details were classified. This report is summarized for the venting category.

Brewer, G.R., ION Propulsion - Propellant Storage and Control Subsystems, Hughes Research Laboratories, Gordon and Breach Science Publishers: New York, 1970.

Interesting concepts for nonwetting fluids are presented, however not much design information was presented. No testing was done to verify calculations.

Brown, C.H., et al, "Feasibility Demonstration of Advanced Attitude Control Systems Quarterly Progress Report, 1 February 1966 to 30 April 1966," Bell Aerosystems Company, AFRPL-TR-67-152, May 1966. Classified report.

> This study is referenced by Bovenkerk, 1969, as containing more detailed information on surface tension devices for venting and acquisition.

Burge, G.W., et al, "Design of Propellant Acquisition Systems for Advanced Cryogenic Space Propulsion Systems,"MACDAC,AIAA Paper No. 73-1287, Contract No. NAS8-27685, November 1973.

> This paper is a synopsis of reports by Burge,and Blackmon, 1973 that are summarized.

DeBrock, S.C., "Spacecraft Capillary Propellant Retention and Control for Long-Life Missions," Lockheed, AIAA No. 68-465, April 1968.

> Concentric perforated plates for center of mass control in a very low gravity environment are discussed. Not enough details are given to be of value.

DeBrock, S.C., "Surface Tension Devices for Management of Space Propulsion System Propellants," Lockheed, 670558, June 1967.

> The report is qualitative with no design data or unique information presented.

DeBrock, S.C., "Development and Flight Experiments with a Capillary Propellant Management System for a Three Axis Stabilized Vehicle," Lockheed, AIAA Jet Propulsion Specialists Conference, November 1972.

> The report describes galleries with screened windows (four 190° channels) in a 62" diameter hydrazine tank. System analysis and design are similar to that described in DeBrock 1970 and 1973. Bubble point acceptance testing was used for the welded assembly. The system is described in Heller, 1971, which is summarized. In fact, the device appears on the cover of that report.

DeBrock, S.C., "Development of a Capillary Propllant Management System for a Sixty-Two Inch Spherical Hydrazine Propellant Tank," Lockheed, AIAA/Aerospace Conference, May 1968.

> This is an interim report. Final results are documented in DeBrock, November 1972, listed above.

DeBrock, S.C., Rudey,C.J. "Agena Primary and Integrated Secondary Propulsion System," Lockheed, AIAA Paper No. 73-1212, F-153, November 1973.

> Propellant management system is briefly described. Device is mainly a restart device, relying upon settling for a refill and thus not strictly applicable to low g fluid transfer. A sponge assembly providing low g refill capability is briefly discussed. Technical details of design, analysis and testing of the sponge are not given.

DiPeri, L. J., "A Resume' of the Management of Liquid Gas Interface Using Surface Tension Technology," Western Filter Company, Inc., AIAA/Aerospace Conference, May 1968.

The information in this paper is contained in more recent reports.

Elliott, J.R., et al, "Booster ACPS Propellant Tanks Determination of Functional Design Requirements for Propellant Acquisition," GD/C, GDCA-76-549-1-124, July 1971

No basic technology information is given and report is not generally available.

Forrester, A.T., Barcatta, F.A., "Surface Tension Storage and Feed Systems for Ion Engines," Electro-Optical Systems, Journal of Spacecraft and Rockets Vol. 3, No. 7., July 1966.

Same, essentially as AIAA Paper 69-249, Trump, G.E., et al, 1966.

Good, R.J., Ferry, G.V., "The Wetting of Solids by Liquid Hydrogen," GD/C, Advances in Cryogenic Engineering, Vol. 8, 1963.

This report analytically demonstrated that cryogens will wet all known solids with a zero contact angle. The information in this basic report has become common knowledge in the field.

Grigorev, G.A., "Wetting Kinetics in Conditions of Intensive Solution," USSR, M21771, Vol. 5, pp. 13-15, 1973.

Basic data on wetting , appearing to apply to liquid metal alloys, from the example given. Detailed information of this type is not needed for designing liquid acquisition systems.

Grigorev, G.A., "Calculation of Thermodynamic Function Changes Occurring during Wetting of Solid Surfaces by Liquids," USSR, BIL-M-21775-(5828.4F), 1973.

Information is not directly applicable to surface tension devices. Applicabilibty appears related to solder or other metallic fluids.

Hall, C.N., "Subcritical, Controlled-Ullage, Cryogenic Tankage Concept," Sundstrand Aviation, Journal of Spacecraft and Rockets, Vol. 1, No. 4, July 1964.

The paper gives a good conceptual description of the use of porous material channels for passing liquid in low gravity. A portion of the liquid is throttled and used to subcool the remaining liquid flow. No data or design details are given, however.

Hastings, L. J., "Cryogen Acquisition in Orbit," NASA-MSFC, NASA TM X-64561, October 1970.

Presents work done between 1967 and 1970 by GDC, Martin and University of Michigan on capillary acquisition, low gravity experimentation on the AS-203, interface stability with foraminous materials, and low gravity boiling heat transfer. Individual source materials are reviewed elsewhere.

Hise, R.E., "Passive Retention Expulsion Methods for Subcritical Storage of Cryogens Test Plan Subscale Dual Screen Liner Retention Expulsion System," MMC, MCR 71-48, Contract No. NAS9-10480, July 1971.

This concept was examined in detail including ground based cryogenic testing in NAS9-12182, Paynter and Page, 1973.

Hollister, M. P., "Considerations on Propellant Expulsion with Passive Surface Tension Techniques," LMSC, AIAA/Aerospace Conference, May 1968.

The information in this paper is contained in more recent reports.

Hollister, M. P., "Propellant Containment Utilizing Screen Mesh and Perforated Plate Surfaces," Lockheed, LMSC-A665481, December 1964.

The report indicates that retention capability of a specific capillary material should be determined by testing (bubble point). Discussion and testing are interesting but specific information is not that useful.

Hollister, M. P., et al, "A Study of Liquid Propellant Behavior During Periods of Varying Accelerations," LMSC, LMSC-A87428, Contract No. NAS9-5174, June 1967.

An analysis of stability, retention, reorientation and refilling of the Apollo Service Module retention system was presented. The analysis was very specific and no unique design information was presented that could be used for general acquisition system design.

Lantz, I.H., "Capillary Action Liquid Oxygen Converter for Weightless Environment," Bendix, AMRL-TDR-63-10, Contract No. AF 33 (616)-8185, January 1963.

For orienting and supplying liquid, concept has limited applicability due to low flow rate capability. Very little data presented.

Moses, R.A., "Time of Vapor Formation and Collapse at the Wall of a Liquid Contained by a Wall and a Capillary Screen," NAR, S-II-193-602-71-061, March 1971.

Internal document not available for normal distribution.

Moses, R.A., et al, "Computed Wicking Rates of Cryogens at Low Gravity for Selected Screens," NAR, Cryogenic Engineering Conference, Georgia Institute of Technology, Paper R-5, August 1973.

Symons, 1974, provides more pertinent information on wicking in screens.

Page, G.R., "Acquisition System Environment Effects Study," MMC, MCR-73-103, Contract No. NAS8-30592, February 1974.

The program will directly aid fluid transfer system design but since the program is still in progress only interim monthly reports have been issued.

Paynter, H.L., "Acquisition/Expulsion System for Earth Orbital Propulsion System Study, Final Report, Volume 1," MMC, MCR-73-97, NAS9-12182, June 1974.

This report is a consolidation of other volumes of NAS9-12182. These volumes, Paynter and Page, 1973, and Fester, 1973 are summarized.

Paynter, H.L., "Passive Retention/Expulsion Methods for Subcritical Storage of Cryogens Summary Report, MMC, MCR-71-37, Contract No. NAS9-10480, July 1971.

More details of the dual screen liner (DSL) concept and the testing required are presented in Paynter and Page, 1973, a five volume study that is summarized.

Paynter, H.L., et al, "Zero-G Liquid Propellant Orientation by Passive Control," MMC, SAE 862D, April 1964.

The significant space data has been superseded, refined or assimilated into the literature, and the report is now obsolete.

Paynter, H.L., Barksdale, T.R., "Criteria for Passive Propellant Control Schemes," MMC, AIAA Paper 69-531, 1969.

Data is presented in more detail in Paynter, 1970, NAS8-21259.

Rex, E.M., "Centrifuge Tests of a Surface-Tension Orientation Device," Rocketdyne, AIAA/Aerospace Conference, p. 89, May 1968.

Good basic report but results have been superseded by more current studies.

Saunders, C.G., "Hydrophobic-Hydrophilic Zero-Gravity Hydrogen Separator Proved Successful on Apollo 11," NASA-Langley, SAE Journal, Vol. 78, No. 1, pp. 74-75, January 1970.

A small device using fibrous teflon and CRES screen was developed to separate hydrogen gas from hydrogenated water for life-support systems. In its present form it does not have application to in-orbit fluid transfer.

Sloma, R.O., "Capillary Propellant Management System for Large Tank Orbital Propulsion Systems," Lockheed, Interagency Chemical Rocket Propulsion Group Eleventh Liquid Propulsion Meeting, Miami Florida, November 1969.

 This system is basically a start basket relying on reorientation and settling for refill and is therefore not applicable to low g fluid transfer.

Smith, J.M., et al, "The Application of Hydrophillic and Hydrophobic Surfaces for Phase Separation in a Low-g Environment," LMSC, Proceedings-Fluid Mechanics, and Heat Transfer Under Low-G, June 1965.

 Only l-g testing was accomplished while later work on this subject (Saunders 1970) included actual low-g testing.

Smylie, R.E., et al, "Liquid Gas Separator for Zero Gravity Environment," NASA-JSC, Patent No. 3,300,949, September 1964.

 The application is for environmental control systems and is not pertinent to in-orbit fluid transfer. Also, similar devices have been built and tested under more current work, reviewed elsewhere, e.g. Saunders, 1970.

Tegtmeyer, R.C., "Final Report Acquisition/Expulsion System for Earth Orbital System Study-Flight Article Volume IV," MMC, MCR-73-97, Contract No. NAS9-12182, June 1973.

 The design and test plan details are not of general use in the design of transfer systems. No technology information is presented.

Trump, G.E., et al, "Surface Tension Storage and Feed Systems for Ion Engines," Electro-Optical Systems Inc., AIAA Paper No. 66-249, Contract No. AF-33(657)-8157, March 1966.

 The concept discussed is similar to Viking 75. The summarized Viking 75 work by Dowdy and DeBrock, 1972 suffices for documenting this type of design.

Vote, F.C., Schatz, "Development of the Propulsion Subsystem for the Viking 75 Orbiter," JPL, AIAA Paper No. 73-1208, November 1973.

 A similar device is adequately described in Dowdy and DeBrock, 1972 which is summarized.

Warren, R.P., et al, "Passive Retention/Expulsion Methods for Subcritical Storage of Cryogens-Final Report," MMC, MCR-71-58, Contract No. NAS9-10480, July 1971.

 The more recent work in NAS9-12182, Paynter and Page, 1973, covers the dual screen liner approach adequately.

Young, C.M., "Cryogen Acquisition in Low G," NASA-MSFC, S&E-ASTN-PFC, August 1973.

The paper discusses some pertinent current problems that are handled in more detail in other sources.

POSITIVE EXPULSION

Boeing, AIAA/Aerospace Conference, May 1968.

A 7.125 inch O.D. stainless steel bellows, 11 inches long was tested in LN_2. Cryogenic bellows evaluation

Techniques,", Boeing, D2-22297, N64-32877, March 1964.

The purpose of this study was to experimentally evaluate metallic bellows and floating piston positive expulsion devices for cryogenic liquids in zero gravity. However, considerable number of improvements in bellows manufacturing techniques have been developed since 1964.

Anderson, R.K. "Apollo RCS Positive Expulsion Tankage Product Improvement Program: Solutions of Command Module and Serve Module Bladder Repositioning Problems, Task E," Bell Aerospace, NASA-CR-114813, Contract No. NAS9-7182, March 1970.

The objective of this task was to increase the expulsion cycle life of Apollo bladders by overcoming bladder-to-shell friction problems. Undersized bladders, similar to that used on the Lunar Module RCS tanks, were evaluated for this application. The bladders used are discussed in detail in Anderson, 1969 which is summarized.

Anderson, R.K., "Apollo Teflon Badder Design," Bell Aerosystems, AIAA/Aerospace Conference, May 1968.

Similar work, by the same author, Anderson, 1969 is summarized.

Bazzarre, D.F. (Commonwealth Scientific Corp.), Petriello, J., (Dilectrix Corp.), Chemical Vapor Deposited Permeation Bladders in Teflon, AIAA/Aerospace Conference May 1968.

The work is similar to Anderson, 1969 in using aluminum coatings to inhibit permeation in N_2O_4 bladders. Also, see Hoggatt, 1971.

Bell, J.E., et al, "Development of Positive Expulsion Systems for Cryogenic Fluids," Beech Aircraft, SSD-TDR-62-14, Contract No. AF 33(616)-6930, May 1962.

   This contract provides groundwork for the later, comprehensive investigation by Pope and Penner (1968), which is summarized.

Bohler, D.M. (Lt.), "Chemical Supplies, Storage and Expulsion of Cryogenic Propellants," WPAFB, PCI 120/6 Section VI-A (Vol. 6, Background Material for the Study of the National Space Power Program, October 1964.

   The paper gives a very brief overview of modes of containment, heat leak, zero gravity consideration and pumping. No design details are presented.

Bredikin, A.B., Oberta, A.F., "Propellant Effects on Attitude Control and Expulsion System Selection in Interplanetary Spacecraft," GE, AIAA/Aerospace Conference, May 1968.

   No useful material was presented in this brief synopsis.

Burns, E.A., et al, "Compatibility of Advanced Elastomers with Hydrazine, Dinitrogen Tetroxide and Fluorinated Oxidizers," TRW, Fluids and Materials Compatibility Symposium, CPIA Publication 240, July 1973.

   A later and more comprehensive discussion of this topic is presented by Martin and Green (1973), which is summarized.

Cabanov, B.T., Lehman, W.F., "Liquid Propellant Positive Expulsion: Rolling Diaphragm Type," Picatinny Arsenal, Technical Report 4073, July 1970.

   This report points out the problems associated with "free floating" rolling diaphragm pistons. Extensive redesign of this system was recommended. Other diaphragm concepts, such as Gleich 1967 are more worthy of attention.

Chinberg, V.L., Perkins, H., "Preliminary Studies of Liquid Oxygen Expulsion Bladders," NASA-MSFC, NASA TM X-53005, 1965.

   See Hoggatt (1968) for more recent developments in LO_2 bladder technology.

Chu, H.N., Unterburg, W., "Life Predictions of Expulsion Bladders Through Fatigue Test and Fold Strain Analysis," Rocketdyne, NASA CR-126658, Contract No. NAS7-506, May 1972.

   The objective of this paper was to develop a method for analyzing fold strains produced by single and double folds. The metals, which are superior with regard to permeation resistance, are inferior with regard to fatigue resistance. The opposite is true of the elastomers. Intermediate plastics (Teflon) were unsatisfactory in both respects for extended duration missions. More complete studies of bladder material problems and characteristics are presented in Hoggatt, 1968 and 1971, Pope and Penner, 1968 and Anderson, 1969.

Coulbert, C.D., et al, "Long Time Dynamic Compatibility of Elastomeric Materials with Hydrazine," JPL, NASA CR 133794, September 1973.

> Tensile properties of EPT-10 and AF-E-332 were determined in air and liquid hydrazine using constant-strain-rate tensile tests over a range of temperatures and elongation rates. Results were used to predict time to rupture for these materials in hydrazine. Experimental results do not appear directly usable as design information.

Courtney, W.J., Schipma, P.B., "A New Handbook for the Aerospace Engineer: NASA Permeability Data for Aerospace Applications," IIT Research Institute, AIAA/ Aerospace Conference, May 1968.

> The work is generally useful, however specific data on permeability related to fluid transfer is presented in Martin and Green, 1973 and Anderson, 1969 which are summarized.

Covington, D.T., Fearn, R.F., "Cryogenic Metallic Positive Expulsion Bellows Evaluation," MMC, NASA CR-72513, Contract No. NAS3-12017, March 1969.

> The objective of this program was to evaluate a welded bellows assembly designed and fabricated by the Solar division of International Harvester. The work indicated that welding techniques for bellows core fabrication require considerable development. More promising are the formed bellows configurations discussed in Stark, 1972 and Lange and Hughes, 1971.

Cox, D.W., Jr., "Development of Ultra Thin Gauge Polymeric Films," Sea Space Systems, NASA CR-72051, September 1966.

> The report describing developments of thin films and cryogenic testing for brittleness, is too narrow in scope to be of use in fluid expulsion system design.

Drust, B., "Potable Water Tank Bladder Oxygen Permeability Tests-Development Test Data," AiResearch, NAR Project Apollo, N.R. P.O. M5JXAZ-450029A, August 1969.

> Bladder test results indicating permeation and diffusion of oxygen through the potable water tank bladder were presented. Results are specifically applicable to one bladder configuration and are not generally applicable to propellant transfer applications. No information is given here on bladder construction.

Fearn, R.F., "Development of a Metallic Bellows Expulsion Device for Fluorine Service," MMC, NASA CR-72980, Contract No. NAS3-12053, October 1971.

> The only useful conclusion from this study it that welded bellows fabrication techniques require considerable improvement.

Feldman, J.W., et al, "Elastomeric Gasket Materials Development for Cryogenic Applications," Whittaker Corp., TP 3-85370, Contract No. NAS8-5053, June 1964.

Evolution of a Teflon-glass laminate for an LO_2 gasket material is presented which is applicable to positive expulsion devices.

Gilbert, L.N., Feemster, J., "A Three Lobe Collapsing Positive Expulsion Unit," Naval Weapons Center, Twelfth JANNAF Liquid Propulsion Meeting, Las Vegas, Nevada, November 1970.

The objective of this paper was to discuss the characteristics of the three lobe collapsing bladder, however considerable progress has been made in the development of reusable, elastomer bladders since this paper was written.

Gleich, D., "Six-Foot-Diameter Metallic Diaphragm for Fluid Storage and Positive Expulsion Systems," Arde, Inc., AIAA Paper No. 70-683, June 1970.

The final report on this program, Gleich (1971) is reviewed elsewhere.

Gleich, D., "Six-Foot-Diameter Multicycle Metallic Diaphragms for Subcritical Cryogenic Fluid Storage and Expulsion," Arde, Inc., AFAPL-TR-70-95, Contract No. AF 33(615)-2827, February 1971.

An Arde program involving cryogenic testing of diaphragms of similar design is summarized (Gleich, 1967).

Gleich, D., "Metallic Positive Expulsion Diaphragms," Arde, Inc., NASA CR 72775, Contract No. NAS3-12026, January 1972.

An Arde program involving cryogenic testing of diaphragms of similar design is summarized Gleich, 1967).

Gleich, D., L'Hommedieu, F., "Recycling Metallic Bladders for Cryogenic Fluid Storage and Expulsion Systems," Arde, Inc., AIAA Paper No. 67-444, July 1967.

The final report on this program Gleich, 1967 is summarized.

Goerke, R.F., "Study of Zero-Gravity Positive Expulsion Techniques," Bell Aerosystems, 8230-933004, Contract No. NAS7-149, June 1963.

This is the first of a series of reports on this four-year contract. For summary and comments, see Sing (1966).

Goerke, R.F., "Study of Zero-Gravity Positive Expulsion Techniques," Bell Aerosystems, 8230-933007, Contract No. NAS7-149, August 1964.

Dynamics and permeation investigations were conducted. This is an interim report.

Gould, R.A., Krzycki,
U.S. Naval Ordnance Test Station, CPIA Seventh Liquid Propulsion Symposium, Vol. 2, October 1965.

> This report indicates that considerable work is required before a usable rolling diaphragm will be available. Work presented in Gleich, 1967 and Martin and Green, 1973 presents the pertinent work done since that time.

Hankins, D.L., Gardner, P.J., "Liquid Oxygen Converter for Weightless Environment," Bendix, WPAFB-ASD-TR 61-534, Contract No. AF 33(616)-6190, November 1961.

> See Hoggatt (1968), summarized elsewhere, for more recent and successful development of polymeric bladders for LO_2 expulsion.

Heilman, R.L., "Propellant Expulsion Bladder for the Saturn V/S-4B," Thiokol Chemical Corp., NASA-CR-102576, Contract No. NAS8-21149, June 1969.

> Considerable development of polymeric expulsion bladders has occurred since this report was published.

Hoggatt, J.T., "Compatibility of Polymeric Films with Liquid Oxygen," Boeing, NASA CR-72134, Contract No. NAS3-7952 (Task I), January 1967.

> The results of this task are included in the report by Hoggatt (1968), which is summarized.

Howell, G., "Status of TRW's Flight and Technology Programs in Positive Expulsion," TRW, AIAA Liquid Rocket TechnicalCommittee, Propellant Expulsion Working Group, Las Vegas, Nevada, November 1971.

> This document is a handout showing viewgraphs and data on the various TRW systems, including diaphragms, bladders, and bellows and is not generally available.

Hulbert, L.E., et al, "State-of-the-Art Survey of Metallic Bellows and Diaphragms for Aerospace Applications, Battelle, AFRPL-TR-65-215, November 1965.

> This report has been superseded by more recent surveys of the state of the art.

Hulbert, L.E., et al, "Final Summary Report on an Investigation of Improved Welded Bellows for Positive Expulsion Applications," Battelle, AFRPL-TR-71-64, Contract No. F04611-69-C-0031, June 1971.

> The objective of this program was to design and fatigue test a welded CRES 347 bellows utilizing the "tilt-edge" configuration, however, the test verification program was not nearly as extensive as that performed by Lange and Hughes (1971).

Hunter, B.J., et al, "Expulsion Bladders for Cryogenic Fluids, Beech Aircraft, Advances in Cryogenic Engineering, Vol. 7, 1961.

This work provided groundwork for the later, comprehensive investigation by Pope and Penner (1968), which is summarized.

Johnson, R.L., "A Study to Analyze the Permeation of High Density Gases and Propellant Vapors Through Single Layer Teflon or Teflon Structure Material & Laminations," TRW, NASA-CR-10935, Contract No. NAS7-505, August 1969.

The problem of, and solution for polymeric film permeability were covered in more detail by Anderson (1969), summarized elsewhere.

Johnson, R.L., "Leakage Through Laminated Bladder Structures with Holes in the Diffusion Barrier," TRW, AIAA/Aerospace Conference, May 1968.

Work was similar to Johnson and Bhuta, 1969 which is reviewed below.

Johnson, R.L., Bhuta, P.G., "A Study to Analyze the Permeation of High Density Gases and Propellant Vapors Through Single Layer Teflon or Teflon Structure Materials and Laminations," TRW, NASA-CR-109768, Contract No. NAS7-505, August 1969.

Diffusion flow rates were analytically determined for laminated positive expulsion bladders. Results of the program are difficult to use since knowledge of the foil defects present in the bladder being evaluated is required. The report is thus not useful as a design tool.

Koch, E.F., "Expulsion Bladder-Equipped Storage Tank Structure," NASA, Patent No. 3,123,248, March 1964.

This patent is very general in its description of the system and offers no useful information for this study.

Lark, R.F., "Cryogenic Positive Expulsion Bladders," NASA-LeRC, NASA TM X-1555, E-4164, April 1968.

Primarily a discussion of other work.

Lee, J.C., Counter-Permeation Phenonenon in Bladdered Expulsion," Rockwell/ Rocketdyne, AIAA/Aerospace Conference, p. 165, May 1968.

The analytical treatment of permeation in bladders indicates that pressurant and propellant vapor can result in formation of large gas bubbles on the propellant side of the bladder. No comparison is given with experimental data. Permeation is discussed in Martin and Green, 1973 and Anderson, 1969, which are summarized.

Levine, N. B., "CNR Expulsion Bladders, " Thiokol Chemical Corp., Contract No. AF 33(615)-5311.

This paper is unnumbered and apparently not generally obtainable. Similar information is presented by Heilman (1969) of Thiokol in a readily-obtainable report.

Lofgren, C. L., Gieseking, D., "Cryogenic Positive Expulsion Diaphragms," Boeing Co., NASA-CR-72732, Contract No. NAS3-11204, October 1970.

This report only indicates that polymeric diaphragm development is far behind that of metallic diaphragms and that work in this area may not be as fruitful as in elastomeric or metallic diaphragms.

Martin, J. W., et al, "Study of Advanced Bladder Technology, OF_2/Diborane, TRW, NASA-CR-115902, Contract No. NAS7-770, July 1970.

The objective of this program was to investigate elstomeric materials for OF_2 and B_2H_6 (Diborane) expulsion bladders, however, considerable development of elastomeric expulsion bladder materials has occurred since this report was written.

Mears, R. B., "Long Term Storability of Propellant Tankage and Components," AFRPL, AFRPL-TR-70-43, May 1970.

White (1971) provides later information on this study.

Mears, R. B., "Condor Expulsion Test, System No. 1, AFRPL, AFRPL-TR-69-107, April 1969.

Centrifuge testing was conducted to evaluate Condor system start capability under axial and transverse load environments. The metallic collapsing expulsion bladders (Expellodyne) were evaluated using alcohol-glycol and Freon as the test fluids. The test was 81% successful. Bladder redesign was recommended. No design details were presented.

Pearson, W. E., "Demonstration of a Combined MMH Hot Gas Pressurization and Expulsion Subsystem, Bell Aerospace, AIAA Paper No. 73-1200, November 1973.

No specific information on the bellows expulsion system performance is presented.

Petriello, J. V., "Evaluation of the Flex Life of a Teflon Co-Dispersion Bladder Film, : Dilectrix Corp., Company Bulletin, September 1971.

This document is not generally available. More information on Teflon co-dispersions can be found in the report by Anderson (1969), summarized elsewhere.

Petriello, J.V., "Modifications in Fluorocarbon Bladder Structures,"
Dilectrix Corp., AIAA/Aerospace Conference, May 1968.

The paper discusses the characteristics of bladder materials as a function of
the relative composition of TFE (Polytetrafluoroethylene) and FEP (Hexa-
fluoropropylene) Teflon. The fluid transfer system designer does not generally
require information at this level of detail.

Pope, D.H., Isakson, V.E., "Positive Expulsion of Cryogenic Liquids," Beech
Aircraft, NASA CR-14095, Contract No. NAS9-513, March 1964.

This contract provided groundwork for the later, comprehensive investigation
by Pope and Penner (1968), summarized elsewhere.

Porter, R.N., Stanford, H.B., "Positive Expulsion Devices Assure Smooth, Reliable
Starts for Spacecraft in Zero G Space," JPL, SAE Journal, August 1965.

No design data given. Report information is superseded by Heller, 1971.

Putt, J.W., "Experience with Teflon Positive Expulsion Bladders for the Surveyor
Vernier Propulsion System," Hughes Aircraft, AIAA/Aerospace Conference,
May 1968.

The subject of laminated teflon bladders has been adequately treated in Hoggatt,
1971 and Anderson, 1969.

Repar, J., "Flight and Experimental Expulsion Bladders for Mariner 69, APCO,
NASA-CR-107435, Contract No. NAS7-100, July 1969.

More recent and comprehensive materials development studies are reported
by Martin and Green (1973) summarized elsewhere.

Ross, R.G, Jr., Womack, J.R., "Slosh Testing of a Spherical Mercury Propellant
Tank With Positive Expulsion Diaphragm," JPL, NASA-CR-133790, JPL-TM-33-632,
July 1973.

Actaul responses deviated greatly from predictions, indicating that considerable
refinement of predictive techniques is required. Because of this the usefulness
of the reported is minimal.

Sargent, D.H., "Advanced Fuel Systems for Ramjet-Powered Vehicles," Atlantic
Research, AFAPL-TR-72-1, F33615-69-C-1849, February 1972.

Similar development work was carried out by Hoggatt (1971), summarized
elsewhere.

Shdo, J.G., Hoggatt, J.T., "Development of Liquid Oxygen Compatitible Adhesive System," Boeing, NASA CR-72502, Contract No. NAS3-17952, December 1968.

A LOX compatible adhesive system for use in Kapton film bladder fabrication was selected from nine adhesives originally selected for screening. A Kel-F elastomeric adhesive was selected based on the three critiera of bonding strength, LOX impact compatibility and adequate flexibility at -320°F. Details of this nature are not required for the current program.

Sievers, R.W., Martin, S.B., "Design Manufacture and Test of a Fluidically Controlled Hydrazine Roll Rate Control System," Ham Std/UAC & Sandia Labs. AIAA Paper 70-650.

A metallic diaphragm is used to expel the fuel, N_2O_4, from a 6-1/8 in. spherical tank. Very little information about the diaphragm appears in this paper.

Sing, D.Y., "Study of Zero-Gravity Positive Expulsion Techniques Design of Welded Bellows," Bell Aerosystems, 8230-933013, Contract No. NAS7-149, November 1966.

The computer programs described in this report were revised on a later contract by Lange and Hughes (1971).

Sirocky, P.J., "Apparatus for Transferring Cryogenic Liquids," NASA-LeRC, Patent No. 3,122,000, February 1964.

No new technology is reported in this patent.

Sirocky, P.J., "Transfer of Cryogenic Fluids by an Expulsion-Bag Technique," NASA-LeRC, NASA TN D-849, April 1961.

This report is very brief and now technically obsolete.

Stevens, C.L., "Positive Expulsion Device," GD/C, Library Bibliographies, September 1965.

This report is a bibliography of reports covering all phases of low g liquid behavior and supply and is not generally available, since it is an internal library document. Pertinent reports were ordered from those cited.

Stump, E.C., Rochow, S.E., "Preparation of Fluoroelastomers for Use with Cryogenic Storable Propellant," Peninsular Chemical Research, Contract No. NAS7-668, February 1969.

The report discusses preparation of tetrafluoroethylene oxide (TFEO) and polytetrafluorethane oxide (PTFEO) as well as several other fluoroelastomers. Fluid transfer system design does not require knowledte of these details.

Takimoto, H.H., Idenault, G.C., "Hydrazine Compatibility with Ethylene-Propylene Elastomers," Aerospace Corp., AD 688-486, Contract No. F04701-68-C-0200, February 1969.

> This work is superseded by more recent work; i.e. AFE-332 is the recommended bladder material for hydrazine according to Martin and Green, 1973.

Wendt, D.A., "High Expansion Metal Bellows with Non-Welded Convolution Edges for Propellant Expulsion Systems," Solar Division, AIAA/Aerospace Conference, May 1968.

> Results on bellows are adequately covered in Stark, 1971, Lange and Hughes. 1971 and Anderson, 1969.

White, H.M., "Long Term Storage Testing of Propellant Tankage," AFRPL, Fluid and Materials Symposium CPIA Publication 240, July 1973.

> Discusses the same information presented in White, 1971.

White, H.M., "Long Term Storability of Propellant Tankage," AFRPL, 1971 JANNAF Combined Propulsion Meeting, Las Vegas, Nevada, October 1971.

> The information provided on positive expulsion systems is comparatively sparse and not particularly useful.

Wiedekamp, K.E., "Liquid Hydrogen Positive Expulsion Bladders," Boeing, NASA CR-72432, Contract NAS3-11192, May 1968.

> A later report by Hoggatt (1971) summarized elsewhere, has made significant progress in the reduction of polymeric film permeability.

Williams, L.O., "Hydrazine Purity Influence on Construction Material Compatibility," MMC, AIAA Paper No. 73-1264, November 1973.

> The composition, purity and decomposition of hydrazine was explored. Useful information was presented, but generally this is of limited applicability to the fluid transfer system design. Work of a similar nature is presented in Coulbert and Yankura, 1972 which is summarized.

Woodruff, W.L., "An Experimental Evaluation of Metallic Diaphragms for Positive Fuel Expulsion in the Atmosphere Explorer Hydrazine Propulsion Subsystem," NASA-GSFC, NASA TN D-7467, December 1973.

> An Arde program involving cryogenic testing of diaphragms of similar design has been summarized elsewhere (Gleich 1967).

OTHER ACQUISITION SYSTEMS

Blackmon, J.B., "Propellant Orientation in Zero Gravity with Electric Fields," MACDAC, Proceedings of Aerospace Forum II Session, IAS 31st Annual Meeting, New York, January 1963.

> This study served as ground work for the more definitive investigation by Blackmon (1965), which is summarized.

Blackmon, J.B., "Dielectrophoretic Propellant Orientation in Zero Gravity," MACDAC, Trans. of Seventh Symposium on Ballistic Missile and Space Technology, Vol. 1, August 1962.

> This program establishes ground work for later work by Blackmon (1965), which is summarized.

Blutt, J.R., "Operating Safety of Dielectrophoretic Propellant Management Systems," Dynatech, NASA CR-101422, Contract No. NAS8-20553, March 1966.

> The material in this report is included in that by Blutt and Hurwitz (1968), summarized elsewhere.

Colaprete, S.J., "Preliminary Investigation for a Zero Gravity Water Separator," NAR, NA-63-1097, September 1963.

> The specific application here is for a small water vortex separator for life support systems. No low-g testing was accomplished and the information presented is not significant to in-orbit fluid transfer.

Fabimian, E.J., Hurwitz, M., "Research and Design of a Practical and Economical Dielectrophoretic System for the Control of Liquid Fuels Under Low Gravity Environmental Conditions," Dynatech, NASA CR-98008, Contract No. NAS8-20553, May 1967.

> No new technical data with regard to dielectrophoretic acquisition system performance is contained in this report.

Hartkopp, S.E., "Zero Gravity Tests of X-15 Nitrogen Tank," USAF, AFFTC-TN-60-34, January 1961.

> Ten zero g aircraft flight tests performed on liquid expulsion tank produced inconclusive results. Neither surface tension or heat transfer considerations appear to have been adequately handled. No quantitative data was presented.

Hurwitz, M., "Electrohydrodynamic Propellant Management for Advanced Centaur," Dynatech, PAS-250, February 1965.

  This report contains proprietary information and is not generally available.

Hurwitz, M., et al, "Zero Gravity Control of Hydrogen and Cesium by Electrical Phenomena," Dynatech, APL-TDR-64-46, Contract No. AF 33(657)-10784, April 1964.

  A more complete discussion of this topic is contained in the report by Blutt and Hurwitz (1968), which is summarized.

Hurwitz, M., Melcher, J.R., "Dielectrophoretic Control of Propellant Slosh in Low Gravity,"Dynatech, NASA CR-98168, Contract No. NAS8-20553, March 1968.

  The report by Blutt and Hurwitz (1968), summarized elsewhere, further develops many of the concepts reported herein.

Jones, T.B., "Hydrostatics and Steady Dynamics of Spatially Varying Electro-mechanical Flow Structures," Colorado State Univ., Journal of Applied Physics, Vol. 45, No. 4, pp. 1487-1491, November 1973.

  Control of dielectric fluids has been discussed in considerable detail (Blutt and Hurwitz 1968), this paper does not add significant new data.

Koval, L.R., Bhuta, P.G., "Slosh Control by Dielectrophoresis," TRW, Institute of Environmental Sciences, Annual Technical Meeting Proceedings, 1966.

  A more complete, and pertinent, discussion of this topic appears in Reynolds and Hurwitz 1969.

Kramer, F., "Pressure Effect of a Sound Wave on a Cryogenic Fluid," NASA-MSFC, NASA TN D-4024, July 1967.

  A positive pressure differential can be observed between a liquid in an open container and the atmosphere outside the container if the liquid is near its boiling point and its surface is subjected to an acoustic sound field. The omnidirectional pressure in the liquid however will not be sufficient to settle liquid at a pre-determined location in the tank. The report generally discredits the work of Wessels in regard to using acoustical pumping for orientation.

Lawler, M.T., Ostrach, S., "A Study of Cyclonic Two-Field Separation," Case Institute of Technology, FTAS-TR-65-2, AFoSR 65-1523, AD 621524, June 1965.

  Later work on this subject is reported by Fleeter and Ostrach, 1966 which is summarized.

Macklin, M., "Water Handling in the Absence of Gravity," TRW, Aerospace Medicine, Vol. 37, October 1966.

No experimental evaluation of the centrifugal and static impingement separator devices proposed were made and no design data is given that would be useful to low g transfer system design.

Melcher, J.R., et al, "Bang-Bang Dielectrophoretic Orientation," MIT and Dynatech, NASA CR-93334, January 1968.

The information in this report is the same as that by Melcher, et al (1969) reviewed below.

Melcher, J.R., et al, "Dielectrophoretic Orientation," MIT and Dynatech, Journal of Spacecraft and Rockets, Vol. 6, No. 1, January 1969.

The pertinent details of this work included in the report by Blutt and Hurwitz (1968), which is summarized.

Melcher, J.R., et al, "Dielectrophoretic Liquid Expulsion," Mass. Institute of Technology and Dynatech, AIAA/Aerospace Conference, May 1968.

More recent work by the authors, in the same area, is reviewed above.

Nice, M., Ostrach, S., "Liquid-Gas Separation and Containment," Case Western Reserve Univ., FTAS/TR 70-49, Grant AFOSR 70-2259, TR, August 1970.

This work is oriented toward vortex liquid-gas separation where the liquid is to remain in the separator. For data on vortex separation which is more pertinent to in-orbit fluid transfer see the summarized report by Fleeter and Ostrach, 1966.

Papell, S.S., "Fluid Dispensing Apparatus and Method," NASA, Patent No. 3,258,918, July 1966.

The magnetic technique is not well developed technology. No design data is presented. Magnetic particles could cause clogging problems when the fluid is used for its final purpose such as engine restart, cooling, etc.

Pearson, C.D., et al, "Liquid Expulsion by Direct Pressurant of a Spinning Propellant Tank," LTV, AIAA Paper No. 69-527, June 1969.

The work reported here concentrated on the problem of potential adverse reactions between the pressurant and oxidizer and data pertinent to in-orbit fluid transfer was not presented.

Pohl, H.A., "Some Effects of Nonuniform Fields on Dielectrics," Princeton Univ. Journal of Applied Physics, Vol. 29, No. 8, August 1958.

This paper describes graphic experiments of dielectrophoretic action but does not relate directly to low-g acquisition.

Reynolds, J.M., "The Use of Electric Fields to Orient Dielectric Liquids in a Zero Gravity Environment," Dynatech, ASD-TBR-63-260, Contract No. AF 33(657)-9423, 1963.

This report discusses the dielectrophoresis phenomenon and has been superseded by more recent treatments of the subject.

Reynolds, J.M., et al, "Design Study of a Liquid Oxygen Converter for Use in Weightless Environments," Dynatech, AMRL-TDR-63-42, Contract No. AF 33(657)-9423, June 1963.

The report by Blutt and Hurwitz (1968), which is summarized, provides more in depth analysis and more extensive experimental data on the oxygen converter system.

Reynolds, J.M., Hurwitz, M., "Electrohydrodynamic Propellant Management Systems for Cryogenic Upper Stages," Dynatech, AIAA Paper No. 66-922, December 1969.

The material contained in this paper is included in the contract final report by Blutt and Hurwitz (1968), which is summarized.

Rosener, A.A., et al, "Technology Development for a Zero Gravity Whole Body Shower," MMC, NASA-CR-112006, Contract No. NAS1-9819, 1971.

The liquid-gas vortex separation work accomplished by Fleeter and Ostrach, 1966, was used here as a base to develop a separator for a space shower application. This unit is too small to be of specific application to fluid transfer and therefore the more basic work of Fleeter and Ostrach is summarized to represent this general technology.

Semon, H.W., "Electrophoresis Separator Combining Centrifugal Separation," GE, B73-10328, Contract No. NAS8-24683, October 1973.

Basic application is to space manufacturing and is not pertinent to the current program.

Wessels, P.S., "Acoustical Pumping in Cryogenic Liquids," GD/Pomona, Design News, 1967.

Same work as covered in Wessels, 1968.

Wessels, P.S.,"Acoustical Pumping in Cryogenic Liquids," GD/Pomona, AIAA Aerospace Conference, "Low Gravity Propellant Orientation and Expulsion," Los Angeles, CA., May 1968.

Acoustical pumping forces are derived for a saturated liquid subjected to acoustic vibration. As indicated by Kramer, 1967, however, acoustical pumping can be used more readily for pressurization than for acquisition.

Wessels, P.S., "Acoustic Pumping for Propellant Management in Space," Space Aeronautics Vol. 51, 75-7, CDC 61108, June 1969.

Same work as covered in Wessels, 1968.

APPENDIX C

NASA – LITERATURE SEARCH – KEY WORDS

A retrospective literature search was conducted using the Convair IBM 370 and CDC Cyber 70 computers and the NASA Data Base. The portion of the Data Base searched was 30 September 1974 back through 1969.

A complete listing of the key words employed in the search is presented below. All documents containing words A thru C were cited plus those matching words D through I with words J through YY.

A.	Weightless Fluids	Y.	Propellant Properties
B.	Settling	Z.	Venting
C.	Expulsion Bladders	AA.	Exhausting
D.	Gravitation	BB.	Interfacial Tension
E.	Gravitational Effects	CC.	Wetting
F.	Reduced Gravity	DD.	Interfaces
G.	Weightlessness	EE.	Instruments
H.	Gravitational Fields	FF.	Cryogenics
I.	Propellant Transfer	GG.	Liquid Flow
J.	Fluids	HH.	Water Flow
K.	Liquids	II.	Fluid Flow
L.	Liquefied Gases	JJ.	Vents
M.	Heat Transfer	KK.	Exhaust Systems
N.	Thermodynamics	LL.	Cryogenic Fluids
O.	Liquid-Liquid Interfaces	MM.	Liquid Sloshing
P.	Liquid-Vapor	NN.	Ullage
Q.	Interface Stability	OO.	Rotating Fluids
R.	Liquid Surfaces	PP.	Rotating Liquids
S.	Hydrodynamics	QQ.	Liquid-Vapor Equilibrium
T.	Capillary Flow	RR.	Free Boundaries
U.	Inlet Flow	SS.	Liquid Oxygen
V.	Fluid Dynamics	TT.	Liquid Hydrogen
W.	Liquid Rocket Propellants	UU.	Refueling
X.	Fluid Mechanics	VV.	Fuel Control

WW. Acquisition

XX. Expulsion

YY. Flow

APPENDIX D

ABBREVIATIONS, DEFINITIONS AND NOMENCLATURE

D.1 INDUSTRY AND GOVERNMENT AGENCY ABBREVIATIONS

ADL	Arthur D. Little
AFAPL	Air Force Applied Physics Laboratory
AFFDL	Air Force Flight Dynamics Laboratory
AFOSR	Air Force Office of Scientific Research
AFRPL	Air Force Rocket Propulsion Laboratory
AIAA	American Institute of Aeronautics and Astronautics
AMRL	Aerospace Medical Research Laboratory
ASME	American Society of Mechanical Engineers
CPIA	Chemical Propulsion Information Agency
GD/C	General Dynamics Convair
GD/FW	General Dynamics Fort Worth
GE	General Electric
JPL	Jet Propulsion Laboratory
LMSC	Lockheed Missiles and Space Company
LTV	Ling Temco Vought
MACDAC	McDonnell Douglas Aircraft Company
MIT	Massachusetts Institute of Technology
MMC	Martin Marietta
NAR	North American Rockwell
NASA-GSFC	Goddard Space Flight Center
NASA-JSC	Johnson Space Center (Formerly MSC)
NASA-KSC	Kennedy Space Center
NASA-LeRC	Lewis Research Center
NASA-MSFC	Marshall Space Flight Center
NBS	National Bureau of Standards
NRC	National Research Corporation
STL	Space Technology Laboratory
SRI	Stanford Research Institute

SwRI	Southwest Research Institute
TRW	Thompson Ramo Woolridge
WPAFB	Wright Patterson Air Force Base

D.2 GLOSSARY OF TERMS

ACS	Attitude Control System
Al Aly	Aluminum Alloy
AS-203	Apollo Saturn No. 203 Flight Vehicle
CRES	Corrosion Resistant Steel
F_2	Fluorine
FEP	Teflon Polymer-Hexafluoropropylene
GHe	Gaseous Helium
GH_2	Gaseous Hydrogen
GN2	Gaseous Nitrogen
GO_2	Gaseous Oxygen
He	Helium
H_2	Hydrogen
LEM	Lunar Excursion Module
LHe	Liquid Helium
LH_2	Liquid Hydrogen
LM	Lunar Module
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
LOX	Liquid Oxygen
MMH	Monomethyl Hydrazine
MLI	Multilayer Insulation
N_2	Nitrogen
N_2O_4	Nitrogen Tetroxide
O_2	Oxygen
RF	Radio Frequency
S-IIB	Saturn Two B Vehicle

S-IVC	Saturn Four C Vehicle
SPS	Service Propulsion System
Superfloc	Trade Name of GD/C Tufted Insulation System
TFE	Teflon Polymer – Polytetrafluoroethylene
T/M	Telemetering
TPS	Thermal Protection System

D.3 NOMENCLATURE

A	area
a	acceleration
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
D, d	diameter
F_{tu}	ultimate tensile stress
G	mass flow flux, $\dot{m}/A$
g	gravitational constant
h	heat transfer coefficient or specific enthalpy
h_f	film heat transfer coefficient
h_{fg}	latent heat of vaporization
k	thermal conductivity
L	length
m	mass
$\dot{m}$	mass flow rate
N	speed, rpm
N_{Gr}, Gr	Grashof number
N_{Re}, Re	Reynolds number
N_{Pr}, Pr	Prandtl number
OD	outside diameter
P, p	absolute pressure
q, $\dot{Q}$	heat transfer rate
Q	volume flow rate

R	radius
t	time
T	absolute temperature
u	velocity
v	specific volume
V	volume
W	weight
$\dot{w}$	weight flow rate
X	fluid quality
Z	compressibility factor
α	thermal diffusivity
ΔH	head
μ	dynamic viscosity
ν	kinematic viscosity (μ/ρ)
ρ	density
σ	surface tension

Subscripts

c	critical
g	gas
i	initial
j	jet
ℓ, L	liquid
o	stagnation
p	propellant
s	saturation
T	tank
u	ullage
v	vapor
w	wall

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